



The North Atlantic Ocean as habitat for *Calanus finmarchicus*: environmental factors and life history traits

Melle, Webjørn; Runge, Jeffrey A.; Head, Erica; Plourde, Stéphane ; Castellani, Claudia; Licandro, Priscilla; Pierson, James; Jonasdottir, Sigrun; Johnson, Catherine; Broms, Cecilie

Total number of authors:
20

Published in:
Progress in Oceanography

Link to article, DOI:
[10.1016/j.pocean.2014.04.026](https://doi.org/10.1016/j.pocean.2014.04.026)

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Melle, W., Runge, J. A., Head, E., Plourde, S., Castellani, C., Licandro, P., Pierson, J., Jonasdottir, S., Johnson, C., Broms, C., Debes, H., Falkenhaus, T., Gaard, E., Gislason, A., Heath, M. R., Niehoff, B., Nielsen, T. G., Pepin, P., Stenevik, E. K., & Chust, G. (2014). The North Atlantic Ocean as habitat for *Calanus finmarchicus*: environmental factors and life history traits. *Progress in Oceanography*, 129 B, 244-284.
<https://doi.org/10.1016/j.pocean.2014.04.026>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.



Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

The North Atlantic Ocean as habitat for *Calanus finmarchicus*: Environmental factors and life history traits

Webjørn Melle^{a,*}, Jeffrey Runge^b, Erica Head^c, Stéphane Plourde^d, Claudia Castellani^e, Priscilla Licandro^e, James Pierson^f, Sigrun Jonasdottir^g, Catherine Johnson^c, Cecilie Broms^a, Hogni Debes^h, Tone Falkenhaus^a, Eilif Gaard^h, Astthor Gislasonⁱ, Michael Heath^j, Barbara Niehoff^k, Torkel Gissel Nielsen^g, Pierre Pepin^l, Erling Kaare Stenevik^a, Guillem Chust^m

^a Institute of Marine Research, Research Group Plankton, P.O. Box 1870, N-5817 Nordnes, Bergen, Norway

^b School of Marine Sciences, University of Maine, Gulf of Maine Research Institute, 350 Commercial Street, Portland, ME 04101, USA

^c Fisheries and Oceans Canada, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, NS B2Y 4A2, Canada

^d Pêches et Océans Canada, Direction des Sciences océaniques et Environnementales, Institut Maurice-Lamontagne, 850 route de la Mer, C.P. 1000 Mont-Joli, QC G5H 3Z4, Canada

^e Sir Alister Hardy Foundation for Ocean Science (SAHFOS), Citadel Hill, Plymouth PL1 2PB, United Kingdom

^f Horn Point Laboratory, University of Maryland Center for Environmental Science, 2020 Horns Point Road, Cambridge, MD 21613, USA

^g National Institute for Aquatic Resources, Technical University of Denmark, Jægersborgs Allé 1, DK-2920 Charlottenlund, Denmark

^h Faroe Marine Research Institute, Box 3051, FO-110 Torshavn, Faroe Islands

ⁱ Marine Research Institute, Skulagata 4, P.O. Box 1390, 121 Reykjavik, Iceland

^j MASTS Marine Population Modeling Group, Department of Mathematics and Statistics, University of Strathclyde, Livingstone Tower, 26 Richmond Street, Glasgow G1 1XH, Scotland, United Kingdom

^k Alfred Wegener Institute for Polar and Marine Research, Polar Biological Oceanography, 27570 Bremerhaven, Germany

^l Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, P.O. Box 5667, St. John's, Newfoundland A1C 5X1, Canada

^m AZTI- Tecnalia, Marine Research Division, Txatxarramendi ugarte, 48395 Sukarrieta, Spain

ARTICLE INFO

Article history:

Available online xxxx

ABSTRACT

Here we present a new, pan-Atlantic compilation and analysis of data on *Calanus finmarchicus* abundance, demography, dormancy, egg production and mortality in relation to basin-scale patterns of temperature, phytoplankton biomass, circulation and other environmental characteristics in the context of understanding factors determining the distribution and abundance of *C. finmarchicus* across its North Atlantic habitat. A number of themes emerge: (1) the south-to-north transport of plankton in the northeast Atlantic contrasts with north-to-south transport in the western North Atlantic, which has implications for understanding population responses of *C. finmarchicus* to climate forcing, (2) recruitment to the youngest copepodite stages occurs during or just after the phytoplankton bloom in the east whereas it occurs after the bloom at many western sites, with up to 3.5 months difference in recruitment timing, (3) the deep basin and gyre of the southern Norwegian Sea is the centre of production and overwintering of *C. finmarchicus*, upon which the surrounding waters depend, whereas, in the Labrador/Irminger Seas production mainly occurs along the margins, such that the deep basins serve as collection areas and refugia for the overwintering populations, rather than as centres of production, (4) the western North Atlantic marginal seas have an important role in sustaining high *C. finmarchicus* abundance on the nearby coastal shelves, (5) differences in mean temperature and chlorophyll concentration between the western and eastern North Atlantic are reflected in regional differences in female body size and egg production, (6) regional differences in functional responses of egg production rate may reflect genetic differences between western and eastern populations, (7) dormancy duration is generally shorter in the deep waters adjacent to the lower latitude western North Atlantic shelves than in the east, (8) there are differences in stage-specific daily mortality rates between eastern and western shelves and basins, but the survival trajectories for cohort development from CI to CV are similar, and (9) early life stage survival is much lower in regions where *C. finmarchicus* is found with its congeners, *C. glacialis* and/or *C. hyperboreus*. This compilation and analysis provides new knowledge for evaluation and parameterisation of population models of

* Corresponding author. Tel.: +47 93004245.

E-mail address: webjoern.melle@imr.no (W. Melle).

<http://dx.doi.org/10.1016/j.pocean.2014.04.026>

0079-6611/© 2014 The Authors. Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

C. finmarchicus and their responses to climate change in the North Atlantic. The strengths and weaknesses of modeling approaches, including a statistical approach based on ecological niche theory and a dynamical approach based on knowledge of spatial population dynamics and life history, are discussed, as well as needs for further research.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Introduction

The northern North Atlantic Ocean is characterised by its circulation and water mass distribution, its extensive latitudinal expanse (from roughly 40 to 75°N) and topography, and its seasonally and geographically varying wide ranges of temperature, salinity and light conditions, which provide a variety of habitats for its biota. Regional differences in physical features lead to differences in the timing and intensity of the annual cycles of primary production, and in the distributions, abundances and seasonal cycles of planktonic grazers and their predators. The distribution of any zooplankton species in the North Atlantic is the manifestation of its ability to maintain itself within this range of conditions, from sub-optimal to optimal, that constitute its habitat.

One approach to understanding the distribution of a species is to examine and define its ecological niche in terms of its range of tolerance based on a series of environmental factors (e.g. [Helaouët and Beaugrand, 2009](#)). Advances in statistical and numerical techniques, such as generalised linear models (GLM) and geographic information systems (GIS), have been applied to quantify species distributions, in species distribution models ([Elith and Leathwick, 2009](#)), habitat distribution models ([Guisan and Zimmermann, 2000](#)) and habitat suitability models (e.g. [Hirzel et al., 2002](#)). Extrapolation to future distribution patterns resulting from habitat change, however, confronts the statistical and ecological assumptions of these models ([Elith and Leathwick, 2009](#)). To gain predictive insight into the consequences of habitat change on the abundance of a species and on shifts in its range and biogeographic boundaries, it is also necessary to understand, at the species level, processes determining population dynamics and life history in relation to environmental changes that affect both physiological and behavioural responses and dispersal patterns. This information can be integrated into complex process models (e.g. [Korzukhin et al., 1996](#)) in the marine realm by means of coupled physical–biological models (e.g. [de Young et al., 2010](#)).

The planktonic copepod, *Calanus finmarchicus*, is one of the most important multicellular zooplankton species in the northern North Atlantic, based on its abundance and role in food webs and biogeochemical cycles. It is the subject of a book ([Marshall and Orr, revised edition, 1972](#)) and over 1000 research articles since its publication. It has been the target species of several previous basin-scale research programs, including investigation of *C. finmarchicus* migrations between oceanic and shelf seas off Northwest Europe (ICOS: e.g. [Heath et al., 1999](#)), Trans-Atlantic Studies of *C. finmarchicus* (TASC: e.g. [Tande and Miller, 2000](#)), the Global Ocean Ecosystem Dynamics program (GLOBEC: e.g. [Gifford et al., 2010](#)), and the ongoing EURO-BASIN program. From the basin-wide programs, in combination with local time series measurements and Continuous Plankton Recorder (CPR) surveys, a tremendous source of information and knowledge of *C. finmarchicus* distribution and life history traits has emerged. Basin scale themes such as the past, present and possible future distribution of *C. finmarchicus*, based on observations and inferences from statistical and process models ([Planque and Fromentin, 1996](#); [Speirs et al., 2005, 2006](#); [Helaouët and Beaugrand, 2007, 2009](#); [Reygondeau and Beaugrand, 2011](#)) have been investigated. In addition, process and modeling studies have studied *C. finmarchicus* phenology, grazing, egg production, over-wintering strategy, mortality and role in

carbon flux budgets (e.g. [Aksnes and Blindheim, 1996](#); [Heath et al., 2000a, 2000b, 2004](#); [Ohman et al., 2004](#); [Melle et al., 2004](#); [Broms and Melle, 2007](#); [Stenevik et al., 2007](#); [Johnson et al., 2008](#); [Broms et al., 2009](#); [Bagoeien et al., 2012](#); [Head et al., 2013a](#); [Hjollo et al., 2012](#)). We review this knowledge of *C. finmarchicus* life history and its North Atlantic habitat in the following section. We then compile, for the first time, the across-basin data sets and provide a synthesis of previously reported and new information on spatially and seasonally resolved demography and life history strategies related to seasonal cycles, development, reproduction, dormancy and mortality across the North Atlantic. We use this information to identify the factors involved in determining distribution and abundance of *C. finmarchicus*, including the important question of connectivity between basin and shelf populations on both sides of the North Atlantic. We consider whether genetic differences between populations in the northeast and northwest/central North Atlantic lead to differences in physiological and ecological responses to changes in environmental conditions. Our overall objective is to provide parameter values and new knowledge of *C. finmarchicus* life history characteristics on a North Atlantic basin scale and, thus to further the development of habitat and basin-scale dynamic models that can be used to predict the effects of climate change on *C. finmarchicus* populations.

The North Atlantic habitat

Ocean circulation is fundamental to the dynamics of a planktonic species' habitat. The North Atlantic surface circulation system is made up of a series of gyres, encircled by strong boundary currents ([Fig. 1a](#)). In the west, the Northwest Atlantic Subpolar Gyre, commonly referred to as the Subpolar Gyre, includes the Labrador and Irminger Seas and is defined by bathymetry to the north and the North Atlantic Current to the south. In the east, the Southern Norwegian Sea Gyre, a cyclonic gyre over the Norwegian Basin of the southern Norwegian Sea, is bounded by bathymetry to the north and by the North Atlantic Current to the south. These two gyres are interconnected, however, and together can be regarded as one basin-scale North Atlantic Subpolar Gyre system, throughout which organisms, including plankton, can be broadly distributed over appropriate time scales, but which nevertheless shows regional differences in ecological characteristics due to the responses of individual species to local conditions.

The Gulf Stream System transports warm and saline water from west to east in the North Atlantic at a latitude of about 40°N in the west (e.g. [Reverdin et al., 2003](#)). At about 54°W, the Gulf Stream splits into two branches, a northern branch connected to the North Atlantic Current and a southern branch connected to the Azores Current. The Azores Current and the southward flowing Canary Current limit the Subtropical Gyre to the north and east. The North Atlantic Current flows to the northeast, with branches flowing into the Icelandic basin and Irminger Sea before the main body enters the Norwegian Sea as the Norwegian Atlantic Current. Thus, the Northeast Atlantic is strongly influenced by northward flowing warm and saline water. Warmer water of Atlantic origin also circulates clockwise around Iceland. Cold Arctic water enters the system from the Arctic Ocean through the Fram Strait as the East Greenland Current and east of Baffin Island as the Baffin Island Current. North of Iceland, the East Icelandic Current separates from the East

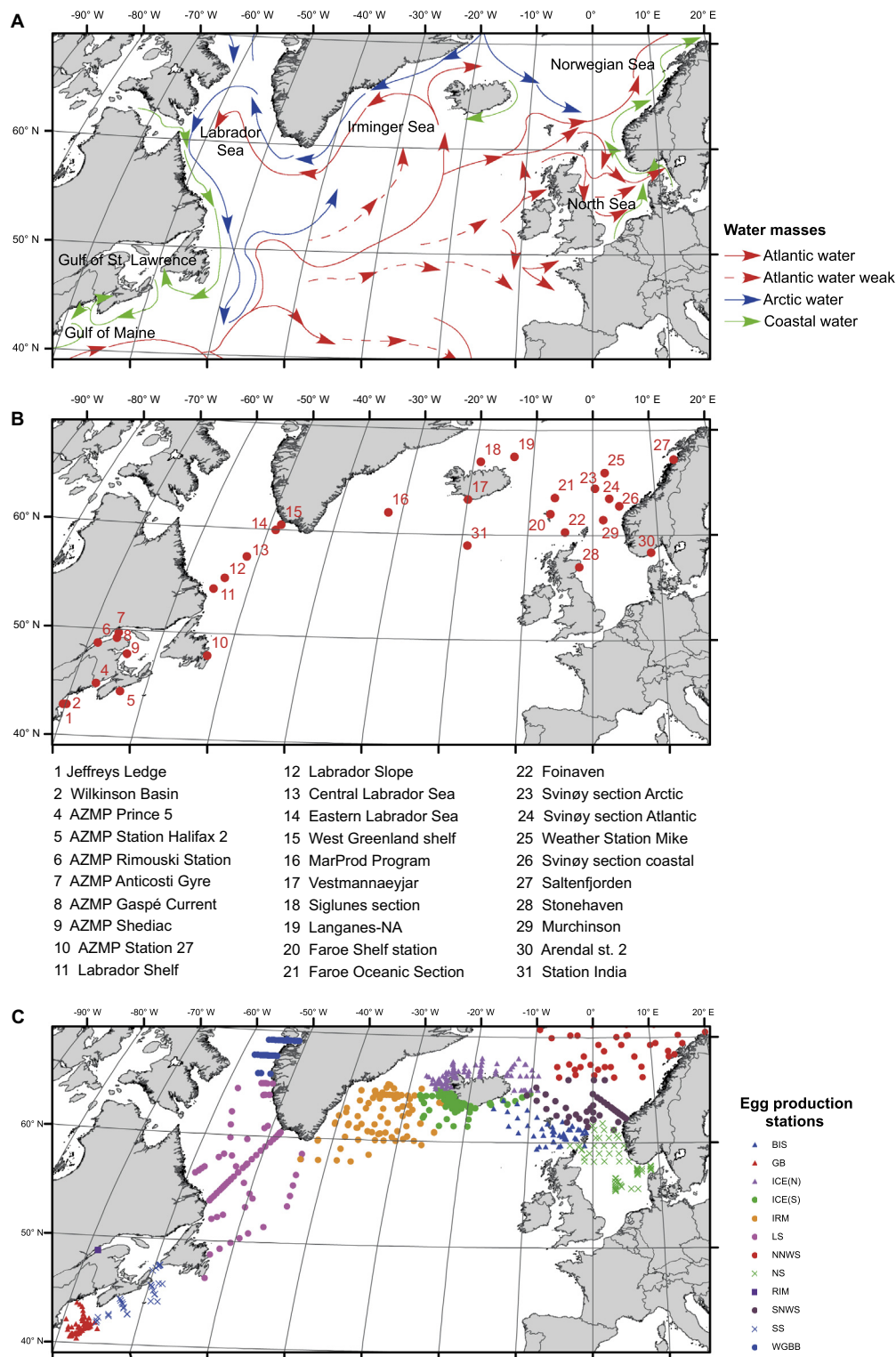


Fig. 1. (A) The northern North Atlantic Ocean, major warm and cold water currents and important seas. After Bagoeien et al., 2012 (B) Locations of demographic stations and transects listed in Table 1. (C) Locations of observations of *C. finmarchicus* egg production rates (and usually adult body size, chlorophyll a concentrations and temperature) analyzed in this study.

Greenland Current, bringing Arctic water eastward into the western Norwegian Sea. The East Greenland Current itself continues southward and meets the warmer Atlantic water of the Irminger Current, with both turning around the southern tip of Greenland and entering the Labrador Sea. This northwesterly flow has a cold water shelf component (the West Greenland Current) and a warmer, deeper offshore component (identified as the Irminger

Current), which provides a major warm water input to the Labrador Sea. The main sources of water to the Labrador Shelf and Slope are the outflows from the Arctic via Hudson Strait and the Baffin Island Current, and the branch of the slope water current that follows the bathymetry westward across the mouth of Davis Strait. These water masses mix off Hudson Strait together forming the inshore (shelf) and offshore (slope) branches of the Labrador

Current moving southwards. Part of the inshore branch enters the Gulf of St. Lawrence through the Strait of Belle Isle, and part continues on to the Newfoundland Shelf and turns around the southeast tip of Newfoundland. A substantial portion of the offshore branch turns to the northeast at the Tail of the Grand Bank to join the North Atlantic Current, but a portion also flows around the Tail of the Grand Bank and along the edge of the Scotian Shelf and Georges Bank (Fratantoni and McCartney, 2010; Loder et al., 1998). Cross-shelf transport of slope water at the Laurentian Channel, Scotian Gulf, and Northeast Channel influences the deep water properties of the Gulf of St. Lawrence, western Scotian Shelf, and Gulf of Maine, and variability in the slope water source, e.g. cold Labrador Slope water vs. warm Atlantic slope water, can drive substantial changes in deep water temperatures on the western Scotian shelf and in the northwest Atlantic marginal seas (Bugden, 1991; Petrie and Drinkwater, 1993; Gilbert et al., 2005). In contrast to the northeast Atlantic, the western Atlantic shelf and slope waters are therefore strongly influenced by southerly flowing cold and low salinity water of Arctic origin. As we discuss later, this contrast in physical regime has implications for understanding east–west differences in effects of climate forcing on species distribution.

The topography of the North Atlantic is characterised by several deep basins: the Labrador Sea basin, the Iceland basin and Irminger Sea, the Norwegian Sea basin in the southern Norwegian Sea, the Lofoten basin in the Northern Norwegian Sea and the Greenland Sea basin. More or less well defined cyclonic gyres are located over these deep basins, which thus offer reduced dispersal for animals within the gyres and possibilities for deep overwintering or deep diurnal migration. In addition to these deep basins are the Norwegian deep fjords (up to 1300 m deep) and basins or troughs (200–400 m depth) in the northwest Atlantic marginal seas (Gulf of Maine and Gulf of St. Lawrence).

The geographical pattern of sea surface temperature (SST) in the North Atlantic is strongly influenced by the Gulf Stream and North Atlantic Current, resulting in a southwest to northeast orientation of isotherms (Figs. 1a and 2a). Because the same SST is found much

farther south in the west than in the east, with very different seasonal and diurnal light regimes, habitats that have similar annual average temperatures in the western and eastern North Atlantic can have biologically quite different conditions. For example, Georges Bank has, on average, temperatures similar to those in the southern Norwegian Sea, but because it is much farther south, light levels in winter are typically sufficient to support primary production. By contrast, on the eastern side of the Atlantic, although temperatures remain relatively high during winter, phytoplankton production ceases, whereas in summer during the growth season, the midnight sun and long days prevail. In addition, in the west cool water temperatures, caused by cold winters and the influence of Arctic waters, allow for the presence of the same visually guided predators much farther south than in the northeast Atlantic.

The North Atlantic pattern of primary production (PP) is strongly related to light conditions and SST, but also to nutrient supply, and to mechanisms of water column vertical stabilisation and grazing. The northeast Atlantic is a typical spring bloom system, although the seasonal cycle of PP differs between deep basins and shelves. In the deep Norwegian Sea basin the pattern of seasonal phytoplankton production has been shown to comply with Sverdrup's concept of critical depth (Sverdrup, 1953), although newer publications indicate that the controlling mechanisms may be more complex or at least regionally different (e.g. Behrenfeld, 2010; Mahavedan et al., 2012). According to the critical depth concept, production will occur when the mixing depth of algal cells is less than a critical depth such that net production is positive. This usually occurs in March–April and the bloom starts in May–June when the pycnocline approaches the upper 30–40 m (Rey, 2004; Bagoeien et al., 2012; Zhai et al., 2012). The timing of the bloom may vary by more than a month among years (Rey, 2004) and the chlorophyll concentration of the upper mixed layer is on average less than 3 mg m^{-3} (Bagoeien et al., 2012). On the Norwegian shelf the water column is permanently stratified by a near surface layer of fresh (light) coastal water or is restricted by shallow bottom depths, so that pre-bloom production and

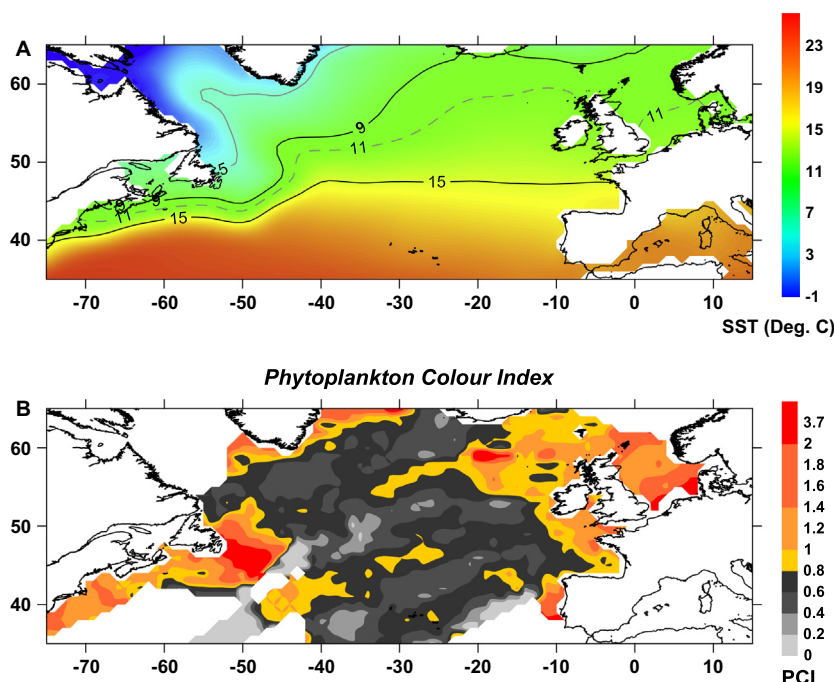


Fig. 2. (A) Annual average sea surface temperature (SST: °C). (B) Annual average phytoplankton colour index from Continuous Plankton Recorder data collected between 2000–2009.

blooms tend to start earlier and to some extent are more intense, providing relatively high chlorophyll concentrations in the water column (Rey, 2004). During the bloom diatoms are the main algal group (Rey, 2004). The post-bloom period lasts until September and is characterised by flagellates, utilising re-cycled nutrients. It has been suggested that pre-bloom levels of phytoplankton are lower than might be expected in the Norwegian Sea due to the grazing activity of the large overwintering population of *C. finmarchicus*, which returns to the surface at this time, and that the intensity of the spring bloom itself is kept low by grazing by the offspring of the overwintered *C. finmarchicus* (Rey, 2004).

In the Irminger Sea, spatial variability in the timing and magnitude of the spring bloom is considerable, reflecting differences in the seasonal timing of stratification of the surface waters (Henson et al., 2006; Waniek and Holliday, 2006; Gudmundsson et al., 2009; Mahavedan et al., 2012; Zhai et al., 2012). On the Iceland and Greenland shelves fringing the Irminger Sea, the growth of phytoplankton usually starts in late April culminating in June and July, whereas in the central region of the Irminger Sea growth usually starts in early May with a maximum in June. As in the northeast Atlantic, timing of the start of the bloom is patchy and may vary interannually by as much as one month, influenced by storms and mixed layer eddy restratification (Mahavedan et al., 2012).

In the northwest Atlantic regions, the timing of spring bloom initiation generally varies with latitude, but there can be substantial departures from this trend among shelf areas due to local or regional processes (O'Reilly and Zetlin, 1998; Platt et al., 2010). Spring and fall blooms tend to start earlier in shallow water, and spring blooms tend to be longer in shallow water (O'Reilly et al., 1987). Interannual variability in bloom timing can be high in the northwest Atlantic (Thomas et al., 2003; Platt et al., 2010). In the Gulf of Maine/Georges Bank region, the spring bloom starts earliest in the shallow coastal areas (January–March), later over Georges Bank (March–April), and latest in the deep basins of the Gulf of Maine and over the shelf edge (April–May) (O'Reilly et al., 1987). On the western and eastern Scotian Shelf, the spring bloom starts in March or April and peaks after about a month, while in the Scotian Slope waters it starts in February or March and peaks in May (Zhai et al., 2011). In the Gulf of St. Lawrence, the spring bloom is earlier in the northeast and southern Gulf (April–May) than in the lower St. Lawrence Estuary (June–July) (reviewed by Zhi-Ping et al., 2010). On the Grand Bank and Flemish Cap, the spring bloom starts in late March or April and peaks after about a month, while on the Labrador Shelf it starts in May (Fuentes-Yaco et al., 2007). The spring bloom starts relatively late (April–June) in the central Labrador Sea, but slightly earlier (April–May) in the northern Labrador Sea, where early stratification is driven by offshore flow of relatively freshwater from the West Greenland Shelf (Frajka-William and Rhines, 2010). Estimates of annual primary production from satellite ocean colour and temperature from 1998–2004 indicate that the highest offshore production in the northwest Atlantic occurs on Georges Bank and in the outflow from the Hudson Strait (ca. $275\text{--}325\text{ gC m}^{-2}\text{ y}^{-1}$), while the lowest production occurs in the Labrador slope waters (ca. $150\text{ gC m}^{-2}\text{ y}^{-1}$) and southern Labrador Sea (ca. $175\text{--}200\text{ gC m}^{-2}\text{ y}^{-1}$) (Carla Caverhill, pers. comm., Platt et al., 2008).

Calanus finmarchicus

The copepod *C. finmarchicus* is the main contributor to mesozooplankton biomass throughout the North Atlantic. Population centres, defined as regions where overwintering populations exceed $15,000\text{ m}^{-2}$, have been identified in the Labrador Sea, northern Irminger Basin, northern Iceland Basin, Faroe-Shetland Channel, eastern Norwegian Sea and Norwegian Trench (Heath et al., 2004). Based on this criterion, slope waters off the Grand

Bank of Newfoundland, the Laurentian Channel of the Gulf of Saint Lawrence, deep basins in the Gulf of Maine, and slope waters of the western Scotian Shelf are also population centres (Plourde et al., 2001; Head and Pepin, 2008; Maps et al., 2012). *C. finmarchicus* makes up >80% of large copepods by abundance in the central Labrador Sea in spring and summer (Head et al., 2003, sampled with a 200 μm mesh net, which in this cold region catches all *Calanus* copepodite stages), about 40–70% of the mesozooplankton community on Flemish Cap, east of the Grand Bank of Newfoundland (Anderson, 1990, sampled with 333–505 μm mesh nets, which excludes the youngest copepodite stages as well as smaller copepod species), and 40–90% of the zooplankton community by abundance in waters around Iceland in summer (Gislason and Astthorsson, 2000, sampled with a 200- μm mesh net which here excludes some of the smaller stages). There are apparently two major overwintering areas, which serve as population reservoirs and distribution centres, in the two subpolar gyres; one in the Labrador/Irminger Seas and the other in the southern Norwegian Sea (Conover, 1988; Planque et al., 1997; Head et al., 2003; Melle et al., 2004; Heath et al., 2008; Broms et al., 2009). These cyclonic gyres are centred over deep ocean basins, so that they can retain populations as they are overwintering at depth, a necessity for *C. finmarchicus* to close its life cycle both spatially and inter-annually (Heath et al., 2004, 2008). From these distribution centres *C. finmarchicus* is transported to the surrounding shelves and shallow seas (e.g. the Labrador, Newfoundland shelves; North and Barents seas) and ultimately to more distant regions (e.g. Scotian Shelf, Gulf of Maine) (Speirs et al., 2006; Heath et al., 2008). There is evidence from genetic analysis that there are two to four distinct *C. finmarchicus* populations, with greatest differences occurring between the northwest/central North Atlantic and northeast Atlantic (Unal and Bucklin, 2010). Toward the Arctic domain, *C. finmarchicus* co-occurs with its larger congeners, *C. hyperboreus* and *C. glacialis*, while in the southeast it co-occurs with the temperate water species, *C. helgolandicus* (Conover, 1988; Hirche, 1991; Head et al., 2003; Melle et al., 2004; Bonnet et al., 2005; Hop et al., 2006; Broms et al., 2009).

Throughout its biogeographic range, *C. finmarchicus* is a dominant grazer and the main prey for numerous planktivorous fish, including herring, mackerel, capelin and young blue whiting and salmon (e.g. Dalpadado et al., 2000; Darbyson et al., 2003; Dommasnes et al., 2004; Skjoldal, 2004; Overholtz and Link, 2007; Smith and Link, 2010; Langøy et al., 2012). The larvae of many fish species also feed, sometimes almost exclusively, on the eggs and nauplii of *C. finmarchicus*, and copepodite stages are important food for the juvenile fish in shelf and shallow sea nursery areas (Runge and de Lafontaine, 1996; Heath and Lough, 2007).

During its life cycle from egg to adult (females, CVIF and males, CVIM), *C. finmarchicus* pass through six nauplius (NI–NVI) and five copepodite stages (CI–CV). The first two naupliar stages do not feed. The life cycle of *C. finmarchicus* is annual in its main distributional area (Conover, 1988; Heath et al., 2000a, 2008; Irigoien, 2000; Hirche et al., 2001; McLaren et al., 2001; Broms et al., 2009; Bagoeien et al., 2012; Head et al., 2013b). In regions influenced by Arctic outflow, however, where water temperatures are low, development rates are reduced and young copepodites (CI–CIII) are found among the older overwintering stages (Broms and Melle, 2007; Heath et al., 2008), suggesting that there is either a multiannual life cycle or an inability to reach stages that can survive the winter within the first season, leading to expatriation (Melle and Skjoldal, 1998). Although there is only one generation per year within the main distributional area within the subpolar gyre (e.g. Labrador Sea, Northern Norwegian Sea) farther south (e.g. Georges Bank) there may be up to three generations per year (Irigoien, 2000; Hirche et al., 2001; McLaren et al., 2001; Plourde et al., 2001; Head et al., 2013b). The number of generations may

vary among years at the same location (Irigoin, 2000) and in some areas (e.g. Newfoundland Shelf) distinct generations are not evident.

The main overwintering stage is the pre-adult CV (Conover, 1988). In the deep basins, *C. finmarchicus* CVs spend most of the year at depths below 400–1000 m (Heath et al., 2000b, 2004; Melle et al., 2004). In the northern Norwegian Sea, overwintering *C. finmarchicus* are most abundant between about 600 and 1200 m, at temperatures less than 2 °C (Edvardsen et al., 2006). In the Iceland Basin, overwintering *C. finmarchicus* reside between about 400 m and the bottom (>2000 m) at temperatures about 3–8 °C, while in the Irminger Basin, they reside between about 200 and 1800 m at temperatures of 3–6 °C (Gislason and Astthorsson, 2000). In the northwest Atlantic, overwintering *C. finmarchicus* occupy a broad and spatially variable depth range, in temperatures ranging from 1 to 10 °C (Head and Pepin, 2008). Overwintering depths are shallowest in Gulf of Maine basins, the Laurentian Channel and in eastern Scotian slope waters (ca. 100–400 m) and deeper in western Scotian slope water (400–950 m) and in Newfoundland slope waters (400–1500 m). In the western part of the central Labrador Sea overwintering depths are variable, but generally <1000 m, while in the eastern Labrador Sea near the Greenland shelf, *C. finmarchicus* overwinters at greater depths, similar to those in the Irminger Sea (Head and Pepin, 2008). Individual *C. finmarchicus* enter dormancy in summer and fall (Hirche, 1996a), carrying with them lipid stores that make up most of their body weight. These lipid stores sustain metabolism during overwintering and subsequent molting and partial development of gonads in mid-late winter (Rey-Rassat et al., 2002). Dormant copepodites are characterised by reduced metabolism and arrested or slowed development (Saumweber and Durbin, 2006). In many locations there is evidence that fourth stage copepodites (CIVs) enter dormancy, with higher proportions of dormant CIV copepodites observed in the northeast Atlantic than in the northwest Atlantic (Heath et al., 2004; Melle et al., 2004; Head and Pepin, 2008). The implications of CIV dormancy have not been rigorously examined, although it is unlikely that CIVs can molt to CVs without feeding since they are significantly smaller. The descent to overwintering depths at Weather Station India occurred during at least two pulses towards the end of each of two cohorts (Irigoin, 2000), whereas elsewhere individuals from different generations may descend over several months (e.g. Johnson et al., 2008).

Arousal from the winter diapause generally occurs in mid-late winter, when most CVs leave dormancy, molt into adults and mate upon returning to the surface (e.g. Melle et al., 2004). Females then lay eggs in response to food levels, for which chlorophyll a concentration is a useful proxy (Runge et al., 2006). The arctic species, *Calanus hyperboreus*, uses internal body stores including lipids to produce eggs without any external food supply (Conover, 1988), but the extent to which internal body stores contribute to egg production for *C. finmarchicus* is still unresolved. In many populations, not all CVs from the new year's generation enter dormancy; some molt on to adulthood, so that reproduction can occur throughout the year (e.g. Durbin et al., 1997; Heath et al., 2008).

In the Norwegian Sea, studies have demonstrated that spawning occurs at relatively low food concentrations and low individual rates before the spring bloom. However, population egg production rates were higher during the pre-bloom period than during the bloom itself, due to the higher abundance of females (Niehoff et al., 1999; Richardson et al., 1999; Stenevik et al. 2007; Debes et al., 2008). Regional differences in the timing and intensity of *C. finmarchicus* reproduction have been observed (e.g., Plourde et al., 2001; Runge et al., 2006; Stenevik et al., 2007; Head et al., 2013a, 2013b), reflecting regional variations in the timing and intensity of spring blooms. These results are mainly based on individual studies that have usually been limited to one or a few

regions; whether responses of females to environmental conditions can be generalised throughout the North Atlantic has not been addressed.

The maximum abundance of CIVs of the first generation has often been observed to occur during the peak of bloom or just after (Hirche et al., 2001; Melle et al., 2004; Bagoeien et al., 2012), and these CIVs must have arisen from eggs spawned before the bloom. On the other hand, during the pre-bloom period, mortality rates are thought to be high due to starvation of first feeding nauplii and/or predation on eggs during the pre-bloom phase, which may include predation by the females themselves (e.g. Ohman and Hirche, 2001; Plourde et al., 2001; Heath et al., 2008). The CIVs–CIIIIs are found exclusively in the upper mixed layer or in the pycnocline, if a subsurface chlorophyll maximum develops during the post-bloom phase (Melle and Skjoldal, 1989; Irigoien, 2000; Melle et al., 2004).

Mortality and survival are key parameters in *C. finmarchicus* population dynamics. In the early stages (eggs, nauplii) they are especially important in determining overall recruitment success (i.e., Ohman and Hirche, 2001; Ohman et al., 2002; Plourde et al., 2009a, 2009b). Survivorship of *C. finmarchicus* is mainly governed by temperature, food availability and/or con-specific abundance, which results in marked seasonal and regional differences in stage-specific mortality patterns (Ohman and Hirche, 2001; Ohman et al., 2002, 2004; Heath et al., 2008; Plourde et al., 2009b). In the northwest Atlantic, the integration of stage-specific daily mortality rates over the entire cohort developmental period revealed significant differences in survival trajectories among seasons and sub-areas, associated with differences in environmental conditions (Plourde et al., 2009b). The use of mortality formulations corresponding to different sets of environmental conditions have enabled modeling of region-specific *C. finmarchicus* population dynamics, a significant step forward in basin-wide biological modeling for the species (Runge et al., 2005; Neuheimer et al., 2010; Maps et al., 2010, 2011).

In the Norwegian Sea studies of predation mortality for *C. finmarchicus* copepodite stages have been conducted to evaluate feeding conditions for pelagic fish stocks and to investigate top down versus bottom up processes in the ecosystem. Analysis of stomach samples have shown herring, mackerel and young blue whiting to be important predators on *C. finmarchicus* copepodites (Dalpadado et al. 2000; Gislason and Astthorsson, 2002; Prokopchuk and Sentyabov, 2006). Consumption by herring has been estimated at about 20–100% of the annual *C. finmarchicus* production (Dommasnes et al., 2004; Skjoldal et al., 2004; Utne et al., 2012). Other potential predatory taxa in the Norwegian Sea are krill, amphipods, cnidarians, chaetognaths, large copepods and mesopelagic fishes. For these taxa reliable estimates of biomass, diet and stomach evacuation rates are generally not known, making their predatory impact hard to estimate. Nevertheless, it is clear that these taxa may also be important predators of *C. finmarchicus* copepodites (Melle et al., 2004; Skjoldal et al., 2004).

Materials and methods

Hydrography and chlorophyll measurements and analyses

CTD probes were used to collect hydrographic data (temperature and salinity) at all sampling stations (Fig. 1b and c). Water samples for measurements of chlorophyll-a concentration were collected using water bottles on a rosette on the CTD or on a hydro-wire. At most sites the hydrographic and chlorophyll samples were taken in concert with the zooplankton net samples. CTD profiling depths and water bottle depths varied among sampling sites. Methodologies for determination of chlorophyll a

concentrations are described in publications or can be retrieved from the data provider associated with each station as shown in Tables 1 and 2. Temperatures ($^{\circ}\text{C}$) were averaged over various depth ranges, while chlorophyll concentrations were either integrated (mg m^{-2}) or averaged (mg m^{-3}) over various depth ranges, as indicated in figure captions. At each site where time series measurements were made, temperatures and chlorophyll concentrations were first averaged over 2-week periods within a given year and then over the 2-week periods for all years.

The basin scale distribution of Sea Surface Temperature (SST, $^{\circ}\text{C}$) was calculated from data available from the British Atmospheric Data Centre (BADC); [HadISST 1.1 dataset (<http://badc.nerc.ac.uk/home/>)]. Monthly SST records (1 degree by 1 degree) or the years 2000–2009 were firstly averaged by year and then used to produce the overall average SST map for the period of reference.

Mapping of *Calanus finmarchicus* distribution at the basin scale

The CPR survey is an upper layer plankton monitoring program that has regularly collected samples (ideally at monthly intervals) in the North Atlantic and adjacent seas since 1946 (Warner and Hays, 1994). Water from approximately 6 m depth (Batten et al., 2003a) enters the CPR through a small aperture at the front of the sampler and travels down a tunnel where it pass through a silk filtering mesh of 270 μm before exiting at the back of the CPR. The plankton filtered on the silk is analysed in sections corresponding to 10 nautical miles (approx. 3 m^3 of seawater filtered) and the plankton microscopically identified (Jonas et al., 2004). In the present study we used the CPR data to investigate the current basin scale distribution of *C. finmarchicus* (CV–CVI). Monthly data collected between 2000 and 2009 were gridded using the inverse-distance interpolation method (Isaaks and Srivastava, 1989), in which the interpolated values were the nodes of a 2 degree by 2 degree grid. The resulting twelve monthly matrices were then averaged within the year and the data log-transformed (i.e. $\log_{10}(x + 1)$). The Phytoplankton Colour Index (PCI), which is a visual assessment of the greenness of the silk, is used as an indicator of the distribution of total phytoplankton biomass across the Atlantic basin (Batten et al., 2003b; Richardson et al., 2006).

Seasonal dynamics of *Calanus finmarchicus*

Seasonal abundance cycles of *C. finmarchicus* were derived from samples taken at sites across the North Atlantic (Table 1, Fig. 1b). The sampling sites include both coastal and oceanic stations and vary from relatively cold to warm water locations. Sampling frequency also differs among sites; the more easily accessed coastal sites were generally visited more frequently than the offshore sites. An overview of sampling sites characteristics, sampling gear and methods is provided in Table 1. Temperatures and chlorophyll concentrations are provided for all sites and details on depth ranges and units are given in Appendix Figs. 1–6.

Dormancy

Dormancy timing was calculated using metrics developed by Johnson et al. (2008). Briefly, entry to dormancy was determined as the date when the CV portion of the total composition of the copepodites and adults comprised 50% of the overall maximum CV proportion, calculated using all years of data at a station. In other words, if the maximum CV proportion was 90% at a given station, the date at which the proportion of CVs was greater than 45% of the total number of copepodites and adults would be the dormancy start date. The end of dormancy was calculated as the first date at which adults constituted more than 10% of all copepodites and adults in a given year for three consecutive dates. This was

done to alleviate spurious estimates of dormancy end that may result from transient increases in the proportion of adults in the population.

Data (see Table 1) were gathered from the AZMP dataset (Johnson et al., 2008; Pepin, Plourde, Johnson, Head, pers. comm.; <http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html>), the TASC time series dataset (Heath et al., 2000a; <http://tasc.imr.no/tasc/reserved/cruiseact/timeseries.htm>), the Svinoy Section and Station M datasets (Melle, pers. comm.) and the Gulf of Maine PULSE and REACH time series datasets (Runge, pers. comm.).

Egg production

Observations of egg production rates (EPR) for female *C. finmarchicus* were compared for different regions of the North Atlantic (Fig. 1c). The regions were diverse in size and sampling frequency, ranging from a fixed time series station in the Lower St Lawrence Estuary, off Rimouski (RIM), where nearly 200 experiments were carried out between May and December from 1994 to 2006 (RIM), to a large-scale survey in the Northern Norwegian Sea (NNWS), where about 50 experiments were carried out between April and June from 2002 to 2004 (NNWS). For this analysis the stations were grouped mostly along geographic lines, with only limited attention being paid to oceanographic features. There is some overlap between regions, however, where stations were sometimes kept together when they were sampled on the same cruise. As well, although not shown in Fig. 1c, some stations other than RIM were occupied more than once during different years and/or in different seasons. An inventory of the experiments used in this synthesis and of the data contributors is presented in Table 2. Some of the data included here have appeared in published papers and the citations are included. Previously unpublished data were also provided by C. Broms, E. Gaard, A. Gislason, E. Head and S. Jónasdóttir.

Egg production in *C. finmarchicus* occurs in spawning bouts, which are of relatively short duration and may occur once or more per day (Marshall and Orr, 1972; Hirche, 1996b). While there is evidence for diel spawning periodicity in the sea (Runge, 1987; Runge and de Lafontaine, 1996), females incubated in dishes for the first 24 h after capture do not always show a consistent night time release of eggs, as they did for *Calanus pacificus* (Runge and Plourde, 1996; Head et al., 2013a). Because of the potential for diel egg-laying behaviour, the vast majority of egg production experiments have been carried out by incubating freshly caught females for 24 h. It has been shown that female *Calanus* that are kept and fed *in vitro* and then transferred to an incubation chamber lay the same number of eggs over the next 24 h whether or not they are fed (Plourde and Runge, 1993; Laabir et al., 1995). Thus, it has been assumed that average egg production rates of freshly caught females are the same during the 24 h following capture as they would have been *in situ* (Runge and Roff, 2000). In this study we include only results from such 24 h incubation experiments, and we term the eggs laid during these 24 h periods “clutches”, even though they may originate from more than one spawning bout, and the number of eggs laid by one female during a 24 h period as the clutch size (CS). In most experiments 20–30 females were incubated individually in separate chambers, and the proportion of females that laid eggs over 24 h is referred to as the “spawning frequency” (SF), which is here expressed as a percentage per day. Egg production rates (EPRs) reported here were calculated by individual contributing investigators either simply as the sum of all of the eggs produced in an experiment divided by the number of females incubated and the average incubation time (generally 1 day), or as the average of the EPRs calculated for each experimental female individually, which takes

Table 1
Metadata for *Calanus finmarchicus* sampling stations and transects in the North Atlantic analyzed in this study. *C. finmarchicus* abundances together with temperature and chlorophyll including details on units and sampling depths are shown in Appendix Fig. A1–A6.

Sampling site	Site No.	Location	Latitude	Longitude	Bottom depth (m)	Water mass	Shelf/Slope / Oceanic	Max. sampling depth (m)	Gear	Mesh size (μm)	Years	No. Stations	Analyses**	Data provider
Jeffrey's Ledge	1	Gulf of Maine	42.83 N	70.31 W	50	Coastal	Shelf	45	0.75-m Ring net	200	2003–2008	1	M/D	BCO-DMO, USA
Wilkinson Basin	2	Gulf of Maine	42.86 N	69.86 W	250	Coastal	Shelf	240	0.75-m Ring net	200	2005–2008	1	M/D/S	BCO-DMO, USA
AZMP lines	3	Gulf of St. Lawrence, Scotian Shelf, Newfoundland Shelf	-	-	-	Coastal/Atlantic	Shelf	Btm. or 1000	0.75-m Ring net	200	1999–2009	108	M	DFO, Canada
AZMP Prince 5	4	Bay of Fundy	44.93 N	66.85 W	95	Coastal	Shelf	Btm. or 1000	0.75-m Ring net	200	1999–2009	1	D	DFO-Canada
AZMP Station Halifax 2	5	Scotian Shelf	44.27 N	63.32 W	155	Coastal	Shelf	Btm.	0.75-m Ring net	200	1999–2009	1	M/D/S	DFO, Canada
AZMP Rimouski Station	6	Lower St. Lawrence Estuary	48.67 N	68.58 W	340	Coastal	Shelf	320	1-m or 0.75-m Ring net	333, 73, 200	1994–2008	1	M/D/S	DFO, Canada
AZMP Anticosti Gyre	7	Northwest Gulf of St. Lawrence	49.72 N	66.25 W	340	Coastal	Shelf	330	0.75-m Ring net	200	1999–2003	1	M/S	DFO, Canada
AZMP Gaspé Current	8	Northwest Gulf of St. Lawrence	49.24 N	66.20 W	185	Coastal	Shelf	180	0.75-m Ring net	200	1999–2003	1	M/S	DFO, Canada
AZMP Shediac	9	Southern Gulf of St. Lawrence	47.78 N	64.03 W	84	Coastal	Shelf	Btm.	0.75-m Ring net	200	1999–2009	1	D	DFO-Canada
AZMP Station 27	10	Newfoundland Shelf	47.92 N	52.98 W	175	Coastal/Atlantic	Shelf	Btm.	0.75-m Ring net	200	2000–2009	1	M/S	DFO, Canada
Labrador Shelf	11	Labrador Shelf	54.22 N	55.04 W	140–200	Arctic	Shelf	100	0.75-m Ring net	200	1995–2006	1–7	M/S	DFO, Canada
Labrador Slope	12	Labrador Slope	55.27 N	53.98 W	1000–3000	Arctic/Atlantic	Slope	100	0.75-m Ring net	200	1995–2006	<7	M/S	DFO, Canada
Central Labrador Sea	13	Labrador Sea	57.37 N	51.80 W	3000–3700	Atlantic/Arctic	Oceanic	100	0.75-m Ring net	200	1995–2006	4–13	M/S	DFO, Canada
Eastern Labrador Sea	14	Labrador Sea	59.99 N	48.90 W	2800–3600	Atlantic/Arctic	Oceanic/Slope	100	0.75-m Ring net	200	1995–2006	0–9	M/S	DFO, Canada
West Greenland shelf	15	West Greenland	60.51 N	48.30 W	130	Arctic	Shelf	100	0.75-m Ring net	200	1995–2006	<5	M/S	DFO, Canada
MarProd Program	16	Irminger Sea	62 N	32.20 W	>3000	Atlantic	Oceanic	>3000	ARIES	200	2001–2002	-	M	Heath et al. 2008
Vestmannaeyjar	17	Southern Iceland	63.37 N	19.92 W	200	Atlantic	Shelf	190	Bongo	200	1997–1998	1	M/D/S	MRI, Iceland
Siglunes section	18	Northern Iceland	67 N	18.83 W	80–1045	Atlantic/Arctic	Shelf/slope	100 or btm.	Bongo	335	1993–1994	8	M/S	MRI, Iceland
Langanes-NA	19	Northeastern Iceland	67.5 N	13.27 W	188–1860	Atlantic/Arctic	Shelf/oceanic	100	Bongo	200	1995–1996	6	M/S	MRI, Iceland
Faroe Shelf station	20	Faroese Shelf	62.05 N	6.62 W	55	Atlantic	Shelf	50	WP-2/Bongo	100, 200	1997, 2004	1	M/D/S	FAMRI, Faroes
Faroe Oceanic Section	21	Southern Norwegian Sea	63.59 N	6.08 W	550–3300	Atlantic/Arctic	Oceanic	50	WP-2	200	1990–2009	11	M	FAMRI, Faroes
Foinaven	22	Faroe-Shetland Channel	60.32 N	4.23 W	500	Atlantic	Slope	330–500	Bongo	200	1997–1998	1	M/D/S	Heath et al. 2000
Svinøy section Arctic	23	Central Norwegian Sea	64.51 N	0.36 E	2932	Arctic	Oceanic	200	WP2	180	1996–2006	1–2*	M/S	IMR, Norway
Svinøy section Atlantic	24	Eastern Norwegian Sea	63.52 N	2.66 E	1453	Atlantic	Slope/oceanic	200	WP2	180	1996–2006	7–8*	M/D/S	IMR, Norway
Weather Station Mike	25	Eastern Norwegian Sea	66 N	2 E	>1600	Atlantic	Oceanic	200	Multinet/WP2	180	1997–1998	1	M/D/S	IMR, Norway
Svinøy section coastal	26	Eastern Norwegian Sea	62.82 N	4.21 E	501	Coastal	Shelf	200 or btm.	WP2	180	1996–2006	4–5*	M/D/S	IMR, Norway
Saltenfjorden	27	Northern Norwegian Shelf	67.23 N	13.65 E	400	Coastal	Shelf	370	WP2	200	1997–	1	M/S	Heath

Stonehaven	28	North Sea, Scotland Shelf	57°N	2°W	47	Coastal	Shelf	45	Bongo	200	1997–2008	1	M/S	et al. 2000 Heath et al. 2000
Murchinson	29	North Sea	61.50°N	1.67°E	170	Atlantic	Oceanic	150	Bongo	200	1997–1998	1	M/D/S	Heath et al. 2000
Arendal st. 2	30	Southern Norway Shelf	58.38°N	8.82°E	105	Coastal	Shelf	50	WP2	180	1994–2010	1	M/S	IMR, Norway
Station India	31	Northeast ATL	59°N	19°W	2000	Atlantic	Oceanic	600	LHPR	270	1971–1975	1	M	X. Irigoien

* Number of stations out of a total of 17, based on watermass distribution.

** M = Mortality, D = Dormancy, S = Seasonal dynamics.

account of differences in incubation times for individual females. For the WGBB most experiments were carried out using prolonged incubation periods (e.g. 36–48 h), often with relatively few females (~10). For several of the analyses carried out here it was necessary to include the results of these prolonged incubations.

As batches of eggs are released into the water column *in situ*, they may hatch and develop, or they may be consumed by local predators, including female *C. finmarchicus* themselves, which are sometimes the most abundant potential predators (Basedow and Tande, 2006). To avoid cannibalism, incubations are generally set up so as to minimise contact between the females and the eggs they are laying. This has been done by the investigators contributing to this work using one of five techniques (see Table 2). In Method A females are incubated individually in 45–50 ml of seawater in 6–10 cm diameter petri dishes. The eggs sink rapidly to the bottom surface, where they are unlikely to be caught up in the females' feeding currents. Method B involves incubating females individually in similar but smaller "Multi-well" chambers, which have a volume capacity of 10–15 ml. In Method C females are placed individually (or in groups of 2 or 3) in cylinders, fitted with mesh screens on the bottom, which are suspended in beakers of 400–600 ml capacity (Gislason, 2005). The eggs sink through the mesh and are thus separated from the females. Method D represents a modification of Method C, in which there is flow of seawater through the chamber (White and Roman, 1992). Finally, in Method E, individual (or groups of 2 or 3) females are incubated in bottles or beakers (up to 1 l capacity), without screening (Jónasdóttir et al., 2005). For Method E the vessels are kept upright and it is assumed that the eggs will sink out and become unavailable to the females relatively rapidly.

There have been relatively few comparisons of these different experimental methods. Cabal et al. (1997) found that female *C. finmarchicus* from the Labrador Sea incubated individually in 50 ml petri dishes (Method A) or 80 ml bottles (Method E) produced similar numbers of eggs after 3 days, although only three experiments were done and over the first 24 h CSs were larger for Method A. They also found that over 24 to 72 h periods groups of females in screened cylinders within large volume chambers (Method C) gave higher egg production rates than did those in chambers without screens (Method E). Runge and Roff (2000) reported egg laying in dishes (Method A) yielded similar egg production rates to those for groups of 10–15 females incubated in 1.5 l screened beakers (Method C). However, the beaker egg production estimates declined dramatically relative to dish estimates in rough weather, presumably due to increased mixing in beakers and therefore higher loss due to cannibalism. More recently, Plourde and Joly (2008) found that suspending a mesh screen within petri dishes 2 mm above the bottom made no difference to the number of eggs produced by female *C. finmarchicus* over 24 h, although it did increase the number of eggs recovered from *Metridia longa* females, which could be seen swimming actively and sweeping the bottom with their mouthparts in the unscreened dishes. In the Northeast Atlantic, at Ocean Weather Station M (included in our Southern Norwegian Sea (SNWS) region), B. Niehoff (pers. comm.) found that females incubated for 24 h in Multi-wells (Method B) had similar CSs to those incubated according to Method C. None of these studies compared all methods and the fact that the NW Atlantic groups have used Method A, while the central and NE Atlantic groups have used mainly Methods C, D or E introduces a question as to whether methodological differences might have contributed to the differences found among the CSs and EPRs in the different regions. Such an analysis is not possible based on the data currently available, however, and the topic will not be considered further in this work, although it merits further attention.

Table 2

Inventory of egg production rate observations in the North Atlantic included in this study. Regions included are Georges Bank (GB), the Scotian Shelf (SS), Rimouski Station (RIM) in the Lower St Lawrence Estuary, Labrador Sea (LS), West Greenland/Baffin Bay (WGBB), Irminger Sea (IRM), area North of Iceland (ICE(N)), area South of Iceland (ICE(S)), area between Iceland and the Shetland Isles (BIS), South Norwegian Sea (SNWS), North Norwegian Sea (NNWS) and the North Sea (NS). Contributing investigators: J. Runge (JR), R. W. Campbell (RC), S. Plourde (SP), E. Head (EH), T.G. Nielsen (TGN), S. Madsen (SM), K. Arendt (KA), R. Swalethorp (RS), A. Gislason (AG), M. Heath (MH), S. Jónasdóttir (SJ), E. Gaard (EG), B. Niehoff (BN) and W. Melle (WM).

Region	Number of egg production experiments				Investigator(s)	Method	Reference
	Spring	Summer	Autumn	Winter			
GB	(Mar–Apr) 48	(May–Jun) 53	–	(Jan–Feb) 18	JR	A	1
SS	(Apr–May) 27	(Jun) 13	(Nov) 8	–	RC	A	2
RIM	(May–Jul) 110	(Aug–Sept) 66	(Oct–Nov) 18	(Dec–Apr) 3	SP	A	3
LS	(May) 35 48 5	(Jun–Jul) 15 32 5	– –	– –	RC EH TGN, KA	A A E	2 4 5, 6, 7
WGBB	(Late Apr–May) 21	(Jun–Jul) 26	–	(Feb–Early Apr) 6	TGN, RS, SM	E	7, 8, 9
IRM	(May–Jun) 52 16	(Jul–Aug) – 21	–	(Nov–Apr) 6 7	AG MH	C C	10, 11, 12 13
ICE(N)	(May–Jun) 127	–	–	–	AG	C	11
ICE(S)	(Apr–Jun) 108 16	– –	– –	(Dec–Mar) 9 –	AG SJ	C D, E	10, 11, 12 14
BIS	(Apr–May) 19 38	– –	(Oct) 4 –	(Dec–Mar) 31 –	SJ EG	E C	15, 16
SNWS	(Apr–May) 85 21 11 4	(Jun) 8 – –	(Oct) – – 3 –	(Dec–Mar) 7 – 12 –	BN EG SJ WM	B, C C E C	17 14 15, 16 18, 19
NNWS	(May) 36 2	(Jun) 6 –	– –	(Apr) 4 –	WM EG	C C	18, 19 18, 19
NS	(Mar–May) 56	(Jul–Aug) 26	(Sep–Oct) 4	(Jan–Feb) 4	SJ	E	16, 20, 21

References to published data are as follows: 1, Runge et al. (2006); 2, Campbell and Head (2000); 3, Plourde and Runge (1993)+unpubl. data; 4, Head et al. (2013a); 5, Nielsen and Hansen (1995); 6, Arendt et al. (2010); 7, Munk et al. (2003); 8, Madsen et al. 2008; 9, Swalethorp et al. (2011); 10, Gislason and Astthorsson (2000); 11, Gislason (2005); 12, Gislason et al. (2008); 13, Heath et al. (2008); 14, Jónasdóttir et al. (2002); 15, Richardson et al. (1999); 16, Jónasdóttir et al. (2008)+unpubl. data; 17, Niehoff et al. (1999); 18, Stenevik et al. (2007); 19, Head et al. (2013b); 20, Jónasdóttir et al. (2005); 21, Jónasdóttir and Koski (2011).

Another point on which investigators differed is how they dealt with small clutches. For the Georges Bank (GB), Rimouski station (RIM) and Scotian Shelf (SS) regions and for the Labrador Sea (LS) data provided by R. Campbell, clutches of <6 eggs were routinely not included in the datasets on CSs, since they were regarded as being the result of interrupted spawning events. These small clutches were apparently very rare (J. Runge, pers. comm.) and indeed for the LS data reported by Head et al. (2013a) clutches of <6 eggs accounted for only 32 of the 1324 clutches observed, i.e. 2%. For regions farther east, however, the proportions of clutches of <6 eggs were generally larger, between 13% (SNWS) and 33% (Northern Norwegian Sea, NNWS). Because of this difference in data reporting, CSs of <6 eggs were excluded from the calculations of average CSs for all regions. Small clutches were, however, included by all investigators in their calculations of EPRs.

Previous studies of egg production have shown a significant link between clutch size and female size (Runge and Plourde, 1996; Campbell and Head, 2000; Jónasdóttir et al., 2005; Runge et al., 2006) and most of the datasets provided for this work included measurements of the prosome lengths for each individually incubated female for each egg production experiment, along with each corresponding individual clutch size (Table 3). One exception to this was in the SNWS region (data from Ocean Weather Station M), for which average female prosome lengths were determined for groups of females that had not been used in experiments, but that had been collected on the same day. In addition, there were

no measurements of prosome lengths for some data from the region “Between Scotland and Iceland” (BIS) and the SNWS and NNWS regions. As well, prosome lengths were not measured for all clutch sizes enumerated at RIM.

Egg production rates for the experiments carried out within a given region were averaged seasonally (Table 2). The rationale for the grouping of months into seasons within each region was based partly on observations of seasonal cycles of temperature and chlorophyll concentration, partly on what could be ascertained from the literature about the timing of the appearance of females at the surface after over-wintering, and partly on the availability of data. The spring months cover the period when water temperatures are increasing, when the spring bloom is starting or is in progress, when diatoms dominate the female diet and when the overwintered (G0) generation of females is abundant in the surface layers. Spring is the time when community egg production rates, although maybe not individual rates, are expected to be highest. In summer, temperatures are higher, the bloom may still be in progress, but the female diet may be more varied, and some females of the new year's generation may be present. In autumn and winter relatively few females are in the near surface layers and phytoplankton levels are generally low (see section ‘Seasonal dynamics of *C. finmarchicus* in relation to chlorophyll and temperature’).

Observations of *in situ* temperature and chlorophyll concentration were made at nearly all experimental stations. The original aim had been to use *in situ* temperatures from 5 m and chlorophyll

Table 3

Inventory of measurements of female prosome length (PL) and clutch size (CS) of more than 5 eggs included in this study. Regions and investigators are as in Table 2. Clutch sizes for WGBB from experiments run for 24 h (8 in spring, 7 in summer).

Region	Number of measurements				Investigator(s)
	Spring	Summer	Autumn	Winter	
GB	(Mar–Apr)	(May–Jun)	-	(Jan–Feb)	JR
PL/CS	335/655	323/930	-	157/302	
SS	(Mar–Apr)	(Jun)	(Nov)	-	RC
PL/CS	773/435	250/131	154/73	-	
RIM	(May–Jul)	(Aug–Sept)	(Oct–Nov)	(Apr)	SP
PL/CS	1989/2434	1332/1383	145/132	8/38	
LS	(May)	(Jun–Jul)	-	-	RC, EH, TGN, KA
PL/CS	2691/1689	1290/632	-	-	
WGBB	(May)	(Jun–Jul)	-	(Nov–Apr)	
PL/CS	318/61	188/39	-	103/0	TGN, SM, RS
IRM	(May–Jun)	-	-	(Dec–Mar)	AG
PL/CS	782/407	-	-	30/0	
ICE(N)	(May–Jun)	-	-	-	AG
PL/CS	2074/1395	-	-	-	
ICE(S)	(Apr–June)	-	-	(Dec–Mar)	AG, SJ
PL/CS	2029/1198	-	-	87/6	
BIS	(Apr–May)	-	(Sep–Oct)	(Dec–Mar)	SJ
PL/CS	448/200	-	30/5	264/71	
SNWS	(Apr–May)	(Jun)	(Sep–Oct)	(Dec–Mar)	BN, SJ, WM
PL/CS	872/1484	54/40	55/20	208/94	
NNWS	(May)	(Jun)	-	(Apr)	WM
PL	630/337	106/40	-	0/44	
NS	(Mar–May)	(Jul–Aug)	(Sep–Oct)	(Dec–Feb)	SJ
PL/CS	767/329	262/166	47/12	21/0	

concentrations integrated to 30 m in this study. Not all data were provided in this form, however. For example, in some datasets temperature data were surface values or 0–10 m or 0–20 m averages and chlorophyll concentrations were sometimes values integrated to 50 m. In Fig. 3 the data were standardized to a comparable format by assuming that surface, 0–10 m or 0–20 m average temperatures were the same as 5 m temperatures, and that the chlorophyll concentrations were uniform throughout the 0–50 m depth range. These assumptions are likely to be most appropriate in spring and winter, when mixed layers are relatively deep.

Mortality and survival estimation

Data were obtained from sampling programs in different regions of the northeast Atlantic and northwest Atlantic, for which there is sampling at fixed stations sampled at least once a month (sometimes 3–4 times a week, e.g., Station M) or along sections once or a few times per year (Table 1, Fig. 1b). In the northwest Atlantic suitable data were collected in the Gulf of Maine (GoM), on the Scotian Shelf (SS) and the Newfoundland Shelf (NLS), in the Gulf of St Lawrence (GSL) and in the Labrador Sea (LS). In the northeast Atlantic appropriate data were available in areas to the south and north of Iceland (the former including Station India), to the north of the Faroe Islands, in the Norwegian Sea (NWS), and in the Skagerrak (Table 1). Data collected during the TASC and MarProd programmes were also included (Heath et al.,

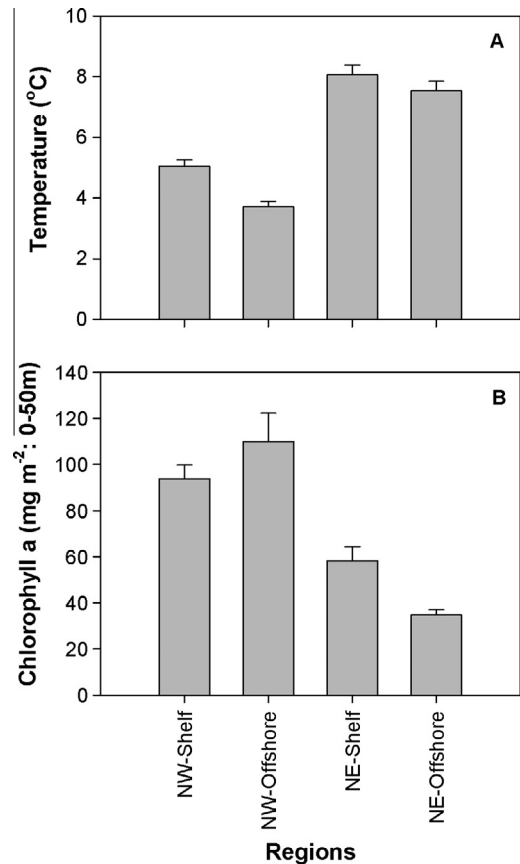


Fig. 3. (A) Surface layer average temperature (°C) and (B) chlorophyll *a* biomass (mg m⁻²) averaged over the surface 50 m in offshore and shelf habitats in the northeast (NE) and northwest (NW) Atlantic. See text for definition of different habitats. Values represent the mean ± standard error.

2000a, 2008). Sampling in the northeast Atlantic (with the exception of TASC and MarProd) and in the Labrador Sea targeted the active part of the *C. finmarchicus* population, with sampling in the near-surface layers (different depth ranges at different sites) whereas sampling in the GoM and in the AZMP region (SS, GSL, NLS) in the northwest Atlantic was over the entire water column, potentially including dormant individuals at depth (Table 1). This difference had to be accounted for before using the VLT method (see below). Because several of the programs did not sample the diapausing component of the population, mortality and survival during the overwintering period were not addressed. Temperature and chlorophyll *a* biomass were estimated for the region-specific surface layer, which was generally shallower on the northwest Atlantic shelves than in other regions.

We adopted the approach of Plourde et al. (2009b) using the Vertical Life Table (VLT) method to estimate mortality and survival for the following stage pairs egg–CI (which actually includes all of the naupliar stages), CI–CII, CIII–CIV, CIV–CV, CV–CVI. The VLT uses the ratio in abundance of adjacent stages, except for eggs, for which female population egg production rate is used rather than abundance. This method is thought to be relatively robust except in highly dynamic or advective environments (Ohman, 2012; Gentleman et al., 2012). In order to minimize biases due to advection and insufficient sampling, which are likely to induce violations to the assumptions associated with VLT, we averaged stage abundances and environmental data for each month at fixed stations (e.g. Halifax 2) or along transects (AZMP) or for oceanographic domains (e.g. LS, NWS, Arctic vs. sub-arctic waters) sampled during each survey. This approach resulted in more robust input data,

reducing the proportion of discontinuous stage structures (stage abundance = 0) or negative mortality estimates that may be caused by patchy plankton distributions or violations of the VLT assumptions (Plourde et al., 2009b). Thus, our meta-analysis was based on replicates of robust averaged stage abundances and environmental data. Only the data collected in Icelandic waters were not averaged because they were collected over only two years. Overall, our data set includes 1233 monthly or transect/regional averages (total $n = 1334$, including Icelandic data), and *C. finmarchicus* shows markedly different phenology across its distributional range (see Figs. Appendix 1–6). We established a common metric to define phases of the population dynamics so that we could compare *C. finmarchicus* populations at the same stage of their seasonal cycles (pre-growth, growth and post-growth periods, see Plourde et al., 2009b), and limit potential biases in our large scale analysis (Gentleman et al., 2012). We chose to restrict our analysis to the population growth period because all development stages should be actively developing and because several sampling programs target the active component of the population in the surface layer, both factors being optimal for the use of the VLT method (Table 1) (Plourde et al., 2009b). We estimated egg production rates per female (EPR) using functional relationships between EPR and chlorophyll *a* that have been reported for each region (Gislason, 2005; Runge et al., 2006; Plourde and Joly, 2008; Head et al., 2013a). EPRs were then combined with the monthly climatology for CIV abundance for each region (location) to calculate the population EPR per square metre. The region-specific population growth period was defined as months with population EPR greater than 15% of the regional seasonal maximum. Using this metric, the population growth period was, for example, from January to August on the SS and from May to September off southern Iceland (not shown). Overall, 57% of all data were collected during the population growth period ($n = 757$).

As in Plourde et al. (2009b), we used the developmental parameters of Corkett et al. (1986) to estimate stage-specific development times (DT) in regions with relatively cold ($<6^\circ\text{C}$) near-surface temperatures during the population growth period, and those of Campbell et al. (2001) for regions that were relatively warm ($>6^\circ\text{C}$). We chose 6°C because this represents the lower limit of the optimal thermal habitat for *C. finmarchicus* (Helaouët and Beaugrand, 2007). In the northwest Atlantic, only the GoM was considered to be a warm habitat, while in the central and northeast Atlantic Corkett's parameters were used for transects/regions located in Arctic water masses north of Iceland, the Faroe Islands and on the part of the Svinoy section where near-surface temperatures were $<6^\circ\text{C}$.

Because our dataset was large, we were able to statistically exclude mortality and survival data that gave unrealistic results which indicated violations of the assumptions and conditions for the application of the VLT method (Plourde et al., 2009b). Based on the cumulative percentile distribution of all mortality and survival values, we determined that mortality values lower than the 5th percentile and survival values greater than the 85th percentile were anomalous, and therefore excluding mortality rates $<-0.20\text{ d}^{-1}$ and survival >2 . Application of this procedure allowed us to objectively exclude between 0% (egg–CI) and 20% (CI–CII, CII–CIII) of the mortality values (depending on the location), and between 5% and 35% of survival values.

The data originated from sampling programs with different sampling strategies and from regions showing markedly different environmental conditions (temperature, food), both being potential vectors of bias in estimating stage-specific abundance and development time (stage duration, DT) and using VLT (Ohman, 2012; Gentleman et al., 2012). We standardized the data in order to minimize these potential biases. Here, we summarize these operations and their rationale as follows:

- We corrected the data for the presence of overwintering stages in the GoM, GSL, on the SS and NLS (northwest Atlantic), which could cause problems with the mortality estimates in stage pairs CIV–CV and CV–CVI (Plourde et al., 2009b). We adapted the seasonal climatology in the activity index (proportion of abundance in 0–100 m/0–bottom) at RIM in the GSL based on the phenology (timing of diapause) in different regions (Plourde, unpublished data, Johnson et al., 2008). This correction had a stronger impact during the early and late phases of the population growth period by decreasing the observed CIV–VI abundance. This adjustment made the abundances of late development stages in the GoM and AZMP comparable with those found in the LS and in the northeast Atlantic where sampling, which was in the upper 0–100 or 0–200 m, and which would have excluded most of the overwintering stages (Østvedt, 1955; Gislason and Astthorsson, 2000; Gislason et al., 2000; Heath et al., 2000b; Melle et al., 2004).
- Sampling the 0–50 m layer along the line off northern Faroe Island and in the Skagerrak likely underestimated total *C. finmarchicus* abundance, especially the late development stages CV and CVI (Gaard and Hansen, 2000). This bias would probably have been even more important later on during the population growth period, when surface temperatures are higher (Williams, 1985; Bonnet et al., 2005; Jónasdóttir and Koski, 2011). Thus, at these locations, we excluded mortality and survival values of stage pairs for the following stages: egg–CI, CIV–CV and CV–CVI.
- We found differences in temperature regimes and phytoplankton biomass among sampling sites and regions, both parameters being important in the determination of DT for most stages in *C. finmarchicus* (Campbell et al., 2001). In the absence of stage-specific parameters for the effect of food limitation on DT, we transposed to *C. finmarchicus* results of an exhaustive study of the effect of food and temperature on development and growth of *C. pacificus* (Vidal, 1980). This study, which included temperatures representative of the whole distributional range of *C. pacificus* (8°C , 12°C , 16°C), showed that the effect of food limitation on DT increased with temperature and developmental stage. We applied these results to *C. finmarchicus*, separating its temperature range into three categories: $<6^\circ\text{C}$, $6\text{--}11^\circ\text{C}$, $>11^\circ\text{C}$. These temperature limits were chosen because based on CPR observations (Helaouët and Beaugrand, 2007), the optimal thermal habitat for *C. finmarchicus* CV–CVI in the North Atlantic is at surface temperatures between 6 and 11°C . Overall, the impact of this food limitation formulation was greater at chlorophyll *a* concentrations $<25\text{ mg m}^{-2}$ in the upper 50 m (or 0.5 mg m^{-3}) and at temperatures above 6°C . This effect was therefore more prominent in the northeast Atlantic where conditions during the population growth period were generally warmer (greater proportion of temperatures $>6^\circ\text{C}$) (Fig. 17). The northeast Atlantic also showed a greater proportion of stations with chlorophyll *a* concentrations $<20\text{ mg m}^{-2}$, while concentrations $>100\text{ mg m}^{-2}$ were more frequently observed in the northwest Atlantic. Under these conditions, the DT for CIVs at temperature in the $6\text{--}11^\circ\text{C}$ range with a chlorophyll *a* concentration $<20\text{ mg m}^{-2}$ would be 3–4 times longer than under non-limiting food conditions. This adjustment diminished the proportion and amplitude of negative mortality estimates for several stage pairs.
- Different temperature regimes might also affect the size of *C. finmarchicus*, which could influence the sampling efficiency for CI, CII and CIII, depending on the net mesh size (Nichols and Thompson, 1991). We used field data collected in the GSL and on SS to establish a relationship between prosome length (PL) of early stages and surface temperature (Plourde, Head, unpublished). PL of both stages decreased significantly with increasing

temperature. We used this relationship to predict PL from surface temperature in our data set, determining a minimal PL above which increasing temperature had no effect (Conway, 2006; Plourde, unpublished). PL was then used to estimate the prosome width necessary to estimate sampling efficiency (Nichols and Thompson, 1991; Conway, 2006). Again, the bias was likely more important in warmer conditions late in the growth period, i.e. generally in the northeast Atlantic. For example, the sampling efficiency for CI and CII with a 200- μm mesh rapidly diminishes between 4–12 °C, with less than 75% and 50% of CI and CII being sampled at temperatures equal to or higher than 12 °C (no effect on CIII). This adjustment reduced the proportion and amplitude of negative mortality estimates in early stages pairs (CI–CII, CII–CIII), and the absolute mortality for the egg to CI transition.

Non-parametric statistical tests (Mann–Whitney to contrast between two groups; Kruskal–Wallis for more than two groups) were used to contrast mortality and survival estimates among different groups (see text below). We used non-linear regression models to describe the relationships between mortality estimates in all stage pairs and temperature, and linear multiple regression models to describe the relationships between mortality in early stages (egg–CI) and temperature, phytoplankton biomass and CVI female (CVIf) abundance.

We contrasted stage-specific mortality and survival among offshore (>1000 m, deep basins) and shelf (<1000 m) domains in the northeast and northwest Atlantic regions. We note, however, that the offshore domain ($n = 44$) was under-represented relative to the shelf ($n = 357$) in the northwest Atlantic, whereas both domains were reasonably covered in the northeast Atlantic (offshore = 146, shelf = 210).

Late stages of sub-Arctic and temperate *Calanus* species and other suspension feeding copepods can ingest their own eggs and nauplii at high rates (see Landry, 1981; Bonnet et al., 2004; Basedow and Tande, 2006), with sizeable consequences on the recruitment patterns (i.e., Ohman and Hirche, 2001; Ohman et al., 2008; Plourde et al., 2009a). Feeding experiments have shown that the large Arctic species *C. hyperboreus* can clear up to 5 l d⁻¹ when fed with *C. finmarchicus* eggs at realistic field concentrations (Plourde unpublished data), suggesting a potential for a high impact of Arctic *Calanus* species on *C. finmarchicus* population dynamics. Therefore, we contrasted stage-specific mortality and survival of *C. finmarchicus* in different 'habitats' defined on the basis of local temperature and on the likelihood of high abundance of *C. glacialis* and *C. hyperboreus* in the surface waters, both indicative of regions being under the influence of cold Arctic water. In the northwest Atlantic *C. hyperboreus* and *C. glacialis* are generally abundant on the shelves and slopes of the Labrador Sea, on the NLS, in the GSL and part of the SS (Head et al., 1999, 2003; Plourde et al., 2003). In the central and northeast Atlantic, these species are important in the Arctic/polar waters off the north coast of Iceland and the Faroe Islands and in the northwestern Norwegian Sea (Astthorsson and Gislason, 2003; Broms et al., 2009; Gislason et al., 2009). These Arctic species are generally active in the surface layer from mid-winter (SS) or early spring (GSL, NLS) to June (SS) or July (GSL, NLS), the end of their active phase in surface waters corresponding roughly to when temperatures reach 6 °C (Plourde et al., 2009a, 2009b; Head and Pepin, 2010; Plourde, unpublished). In the northeast Atlantic, *C. hyperboreus* and *C. glacialis* are present in surface waters from April to July, a pattern similar to the one observed for the GSL and NLS (Hirche, 1997; Melle and Skjoldal, 1998; Astthorsson and Gislason, 2003). In this analysis, we therefore combined these spatial and seasonal patterns to classify our data into the following 'habitats': (1) 'habitats' with temperatures <6 °C with high ($n = 235$) or low ($n = 150$) likelihood

for *C. finmarchicus* to co-occur with *C. hyperboreus* and *C. glacialis*, and (2) 'habitats' with low abundance of *C. hyperboreus* and *C. glacialis* with temperatures 6–11 °C ($n = 272$) or 11–16 °C ($n = 97$). Given the importance of mortality and survival during the egg and naupliar stages in determining the overall cohort development success (Plourde et al., 2009b), this analysis primarily focused on stage pair egg–CI.

Results for all stage pairs were integrated into survival trajectories specific to each region or 'habitat' as in Plourde et al. (2009b). We used the average population EPR during the population growth period across all study sites in the North Atlantic (50,000 eggs m⁻² d⁻¹) to normalise the survival trajectories to a common scale to allow for regional/habitats comparisons. This comparison is not intended to provide actual predictions of survival *in situ*, but is rather a way of showing the effects of varying mortality values under idealised (i.e. unchanging) conditions.

Results

Basin scale habitat characteristics: hydrography and chlorophyll

The 15 °C surface isotherm, from approximately 40° latitude (south of Long Island, New York) in the west and at about 47° latitude in the east (south of Brittany, France), delimits the southern edge of the northern North Atlantic (Fig. 2a). The coldest surface temperatures occur in the Labrador Sea and off the east coast of Greenland. The 11–15 °C annual average surface temperature occurs in a narrow band between southern New England and Long Island in the west, expanding in the drift path of the Gulf Stream, to include a large area of the deep North Atlantic basin south of Iceland, the North Sea, and coastal shelves of Great Britain.

The annual phytoplankton colour index (i.e. PCI, Fig. 2b), a relative index of phytoplankton biomass as sampled by the silk mesh in the CPR, shows no obvious correspondence with the annual pattern of sea surface temperature in the northern North Atlantic. Instead, it indicates that the areas of highest phytoplankton biomass occur at the shelf margins, including the Gulf of Maine, Grand Bank, North Sea and the shelf north and west of the British Isles. Higher phytoplankton biomass is also indicated in Denmark Strait. In general, surface phytoplankton biomass is lower in the deep, central North Atlantic basin, with the exception of the deep water south of Iceland.

Phytoplankton data from the *Calanus* sampling stations generally corroborate the annual patterns of PCI shown in the CPR data, although they indicate that phytoplankton biomass is lower in the northeast Atlantic than in the northwest, except in the northern Norwegian Sea. Two independent regional analyses of the environmental data were carried out. For the first, surface layer averaged temperature and chlorophyll a biomass during the *C. finmarchicus* population growth period (Fig. 3) were calculated for the stations used in the analyses of mortality and survival. Surface layer temperatures were significantly higher in the northeast Atlantic than in the northwest (Mann–Whitney test, $p < 0.0001$), but similar in offshore and shelf habitats within the northeast and northwest Atlantic habitats (Mann–Whitney test, $p > 0.05$). On the other hand, chlorophyll a biomass was greater in both offshore and shelf habitats in the northwest Atlantic than in the northeast (Kruskal–Wallis test, $p < 0.0001$). For the second analysis, near surface temperatures and integrated chlorophyll standing stocks (0–30 m) were calculated by season using data from stations where *C. finmarchicus* egg production rates were measured (Fig. 4). Average 5 m temperatures were highest in summer within each region, and in all seasons and regions they were generally between 4 and 10 °C although they were below 4 °C four regions: the Scotian Shelf (SS), Labrador Sea (LS) and West Greenland Baffin Bay (WGBB) in spring, and Rimouski (RIM) in winter, and above 10 °C at one

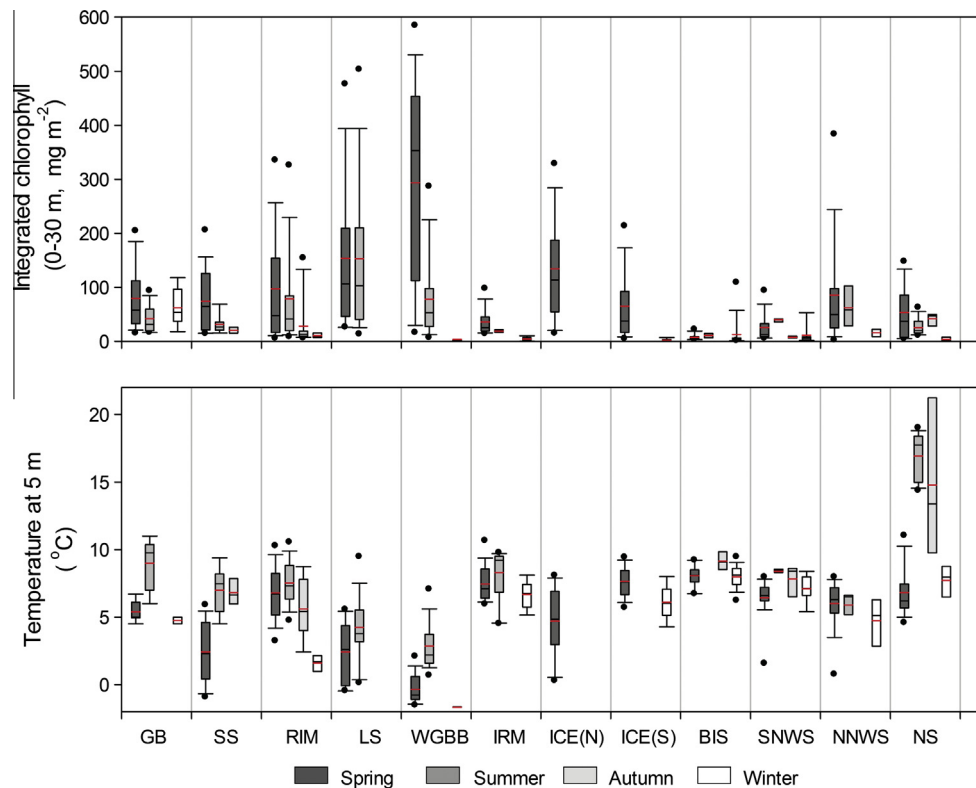


Fig. 4. (A) Average (red horizontal line) 0–30 m integrated chlorophyll concentrations (mg m^{-2}) and (B) Surface layer (0–20 m) temperatures corresponding to regions across the North Atlantic where egg production rates were measured. Black horizontal line denotes median, vertical box boundaries show 25th and 75th percentiles, whiskers indicate 90th and 10th percentiles and filled circles 5th and 95th percentiles. The 0–30 m chlorophyll concentration for the NS in autumn was excluded because in autumn the females reside at 37 m (S. Jonasdottir). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

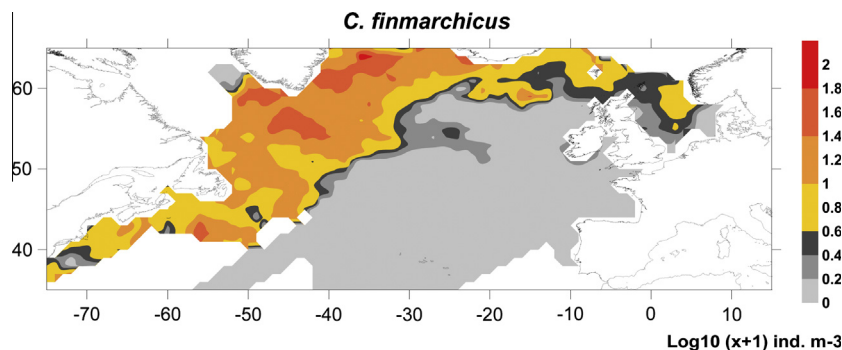


Fig. 5. Annual distribution and abundance of *Calanus finmarchicus* from Continuous Plankton Recorder data collected between 2000–2009.

station the North Sea (NS) in summer and autumn. Most regions were not sampled in every season, but where data are available, integrated chlorophyll concentrations were highest in spring or summer, with the spring months coinciding with the early to mid-bloom period, and the summer months to the mid- to post bloom period. The highest average springtime chlorophyll concentration was near Iceland, north of 65 °C (ICE(N)) where the average 0–30 m value was 4.6 mg m^{-3} , the lowest was in the southern Norwegian Sea region, where it was 1.1 mg m^{-3} . Chlorophyll concentrations were generally low in autumn and winter. The Georges Bank (GB) region, located relatively far south with high winter light levels, was anomalous in that integrated chlorophyll concentrations were relatively high in winter (Jan–Feb).

Distribution of *Calanus finmarchicus* by CPR sampling

The spatial distribution of the log-transformed mean annual abundance for *C. finmarchicus* from CPR collections between 2000

and 2009 is shown in Fig. 5. The abundance of *C. finmarchicus* is highest in the western part of the Atlantic basin particularly off the Scotian Shelf, the southern Labrador Sea, south of Greenland and in the Irminger Basin. The data show lower abundance in the eastern Atlantic, where it is restricted mainly to northern regions.

Seasonal dynamics of *Calanus finmarchicus* in relation to chlorophyll and temperature

Detailed descriptions of the seasonal cycle and associated environmental variables at the sampling stations compiled in Table 1 are provided in the appendix (Figs. A1–A6). Here we explore general demographic patterns (abundance, recruitment timing and dormancy timing) of *C. finmarchicus* populations across the North Atlantic.

Two indices of abundance at the study sites across the North Atlantic were calculated. The annual maximum abundance of all copepodite stages combined (Fig. 6) was highest

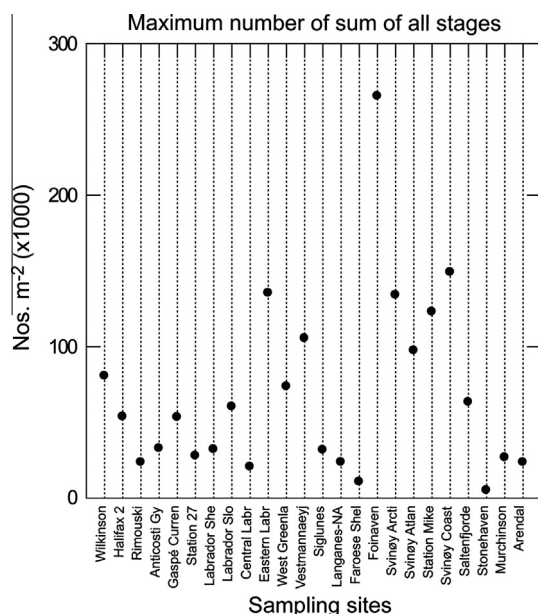


Fig. 6. Mean annual maximum number of sum of all *Calanus finmarchicus* copepodite stages, representing the highest abundance recorded for a single 14 day period during the year, at demographic stations in the North Atlantic (Table 1; Fig. 1B). If there is more than one year in the time series the value represents the mean of all years. Depth range for abundances is given in Table 1.

($135\text{--}265 \times 10^3 \text{ m}^{-2}$) at the southern and eastern Norwegian Sea, southern Iceland shelf and eastern Labrador Sea stations. Differences in abundance could not be simply explained by location on shelves or over deep ocean basins. The relatively high abundance observed at Foinaven is likely due to the fact that here sampling was down to the bottom (500 m), where dormant copepodites would have been captured. The autumn and winter mean annual maximum abundance of stage CV (Fig. 7) shows much higher abundances (on average $10\text{--}30 \times 10^3 \text{ m}^{-2}$) along the western North Atlantic shelves and at a Norwegian fjord station. Abundances in Wilkinson Basin in the Gulf of Maine are notably higher than at any other shelf site and are similar to abundances of stage CV found at depth in the Norwegian and Irminger Seas (Heath et al., 2004). These high shelf abundances represent overwintering stage CVs in areas where the sea is deep enough to allow overwintering to occur. Other sites in the central and eastern Atlantic are either too shallow (e.g. Arendal, Stonehaven) for overwintering, or are very deep (e.g. Station Mike), in which case the overwintering stage CVs were deeper than the depths sampled at sites used in this study. Data from

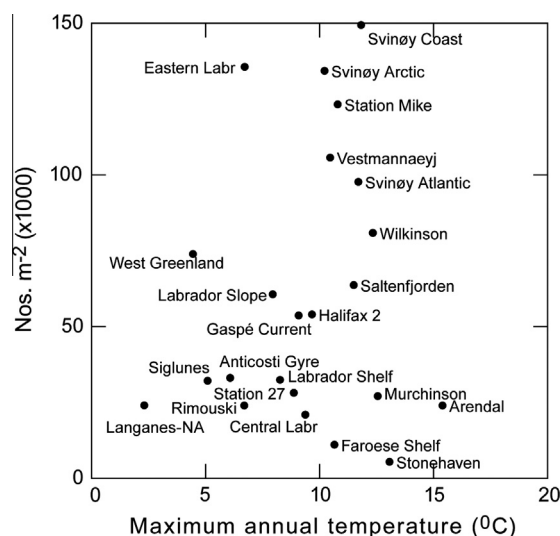


Fig. 8. Mean annual maximum number of sum of all copepodite stages of *Calanus finmarchicus* plotted against mean annual maximum temperature at the demographic stations in the North Atlantic (Table 1; Fig. 1B). Maximum annual temperature is the highest recorded surface layer temperature for a single 14 day period during the year. If there is more than one year in the time series this will be the mean of all years. Depth range for temperatures is given by axes labels in Appendix Figs. 1–6. Station at Foinaven excluded due to inclusion of the overwintering population by sampling to the bottom.

the overwintering period in the Labrador Sea are not shown here, but there individuals would have been at depths greater 0–100 m, which is the depth range that was used for the Labrador Sea data presented here (Head and Pepin, 2008; Head et al., 2013b).

Maximum abundances of *C. finmarchicus* showed a positive relationship with the annual maximum temperature in the surface layer (see axes labels in Appendix Figs. 1–6 for actual depth range of temperature measurements, Fig. 8). Maximum temperature gives a measure of habitat suitability if there is an upper temperature limit above which population growth, reproduction or survival are hampered. Abundances of *C. finmarchicus* peaked where maximum temperatures were around $12\text{--}13^\circ\text{C}$ (Fig. 8). Abundances were both high and low at higher maximum temperatures and invariably low at lower maximum temperatures. If the very near shore and shallow stations of the North Sea and Faroes are excluded, the maximum abundance of *C. finmarchicus* increased exponentially for all maximum temperatures measured at the sites included here.

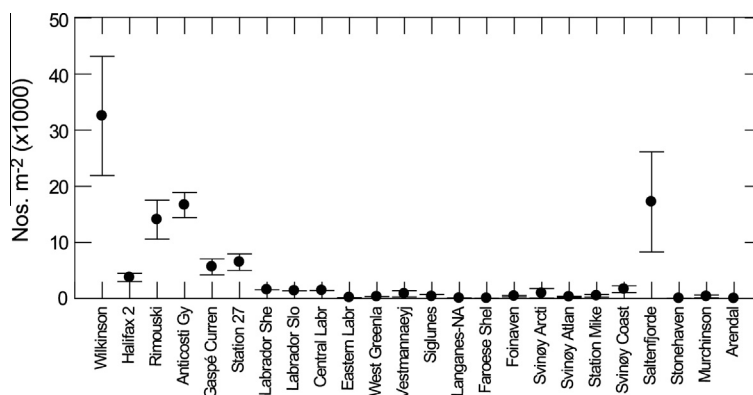


Fig. 7. Average number of stage CV of *Calanus finmarchicus* from mid-October to end of February at demographic stations in the North Atlantic (Table 1; Fig. 1B). Error bars are standard errors. Note that in deep basin stations most CVs are below sampling depth and the figure cannot be used to compare deep ocean and shelf overwintering populations of *C. finmarchicus*.

The timing of recruitment to stages CI–III of the first generation (G1) was investigated by plotting the time of maximum abundance of CI–CIII versus the maximum annual water temperature in the surface layer and the time of maximum chlorophyll concentration (Fig. 9). At all sites, except at the Faroese and Rimouski stations, maximum number of CI–CIII occurred during or after the peak in chlorophyll concentration. There was a weak positive correlation between the times of occurrence of the chlorophyll and CI–CIII maxima (Fig. 9) and a strong, positive relationship between temperature and the timing of recruitment to CI–CIII, so that recruitment at the western North Atlantic sites was up to 3.5 months later than at the eastern Atlantic sites. The sites that showed delayed timing of CI–CIII recruitment relative to the timing of the bloom (sites in upper left corner of Fig. 9, upper panel), were sites with low temper-

atures, suggesting that low temperature may cause a mismatch between *C. finmarchicus* recruitment and the bloom (Broms et al., 2009) (but see also section 'Mortality and survival of *Calanus finmarchicus*' for potential effects of *Calanus* congeners on survival of *C. finmarchicus* early stages). There was no apparent relationship between temperature and the timing of the bloom (not shown).

Dormancy

Considerable variability in the timing of dormancy across the range of *C. finmarchicus* has been recorded (e.g. Planque et al., 1997; Hind et al., 2000; Johnson et al., 2008). Using the dormancy timing metrics described by Johnson et al. (2008), we calculated dormancy entry and exit dates of *C. finmarchicus* for 15 time series data sets throughout the North Atlantic (Fig. 10a and b). In general, the start date of dormancy was more variable than the end date, and the northwest Atlantic had more variability in timing than the northeast Atlantic over similar spatial scales. The dormancy metrics indicated that *C. finmarchicus* enters dormancy later at the northwest Atlantic sites but that the timing of arousal occurs over a relatively short period in late winter (20–60 d) across all stations. In the northwest Atlantic, the major exceptions are the Rimouski and Shediac stations in the Gulf of St. Lawrence, but these may be skewed by the absence of sampling in late winter due to the presence of ice cover. In the northeast Atlantic, the very late exits from dormancy at Foinhaven and Vestfjorden (10 and 15 in Fig. 10) are likely due to local effects on the calculation of dormancy exit times, involving the possible inclusion of a high number copepodites that may have been *C. helgolandicus* or the short length of the time series (<2 yr). Inclusion of *C. helgolandicus* will be a general problem in time series from the North Sea and south of the Norwegian Sea, unless *C. helgolandicus* have been identified (Bonnet et al., 2005). Around Iceland and farther west the numbers of *C. helgolandicus* are small. The data suggest that duration of dormancy, from time of entry to time of exit, is shorter in the western North Atlantic than in the eastern North Atlantic. Our estimate of the median duration of dormancy is 200 d in the northwest Atlantic and 250 d in the northeast Atlantic (270 d if two outliers, Iceland and Faroes, are excluded). There are no time series with sufficient temporal resolution to make these calculations in the middle of the Atlantic (e.g. in the Irminger and Labrador Seas).

Egg production

Broad-scale regional differences in egg production rate (EPR), clutch size (CS), spawning frequency (SF) and prosome length (PL) were examined by averaging all observations carried out within a given region during a given season (Fig. 11). Average female egg production rates were generally highest in spring and summer within regions, and the spring and summer rates were generally higher west of the Irminger Sea (in the GB, SS, RIM and LS regions)¹ and in the ICE(N) region than in the Irminger Sea (IRM) or farther east. One exception to this east–west pattern was the WGBB region, where rates were lower than in other western regions, particularly in spring, when chlorophyll concentrations were very high and temperatures, very low (Fig. 4). Egg production rates were relatively high in winter on GB, but no females laid eggs in experiments carried out during winter in the RIM, IRM and SNWS regions. Average experimental clutch sizes were highest at RIM and in the LS. Spawning frequencies were generally lower in autumn and winter than in spring and summer, but relatively high for GB and NNWS (73% d⁻¹ and 78% d⁻¹) in winter and low (13% d⁻¹) for SNWS in summer. The highest average female prosome lengths were in the SS, RIM, LS and IRM regions and the lowest, in the North Sea (NS).

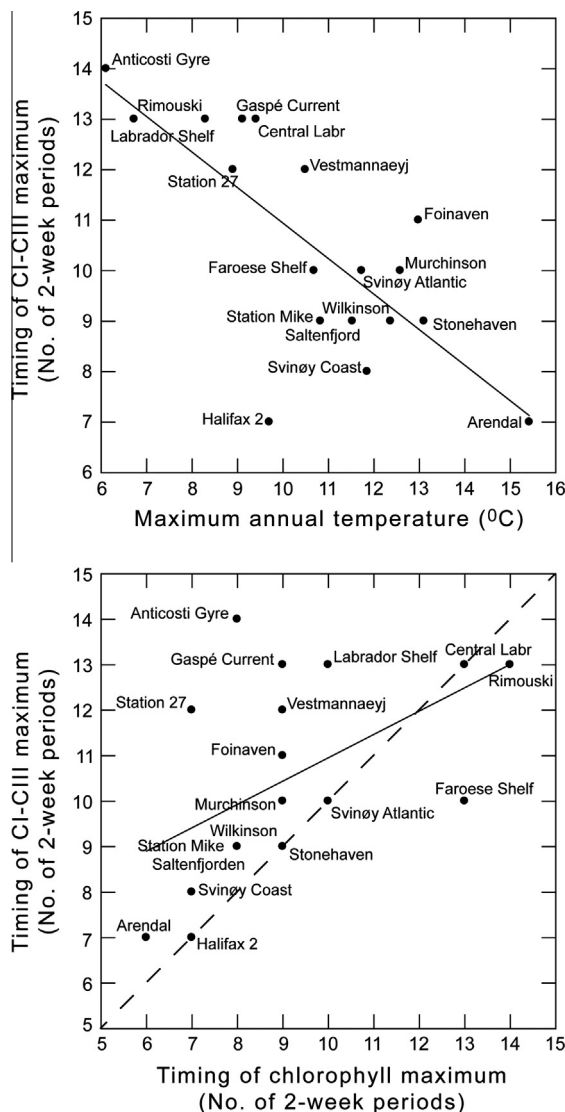


Fig. 9. (A: upper panel) Timing of *Calanus finmarchicus* CI–CIII maximum plotted against maximum temperature (as calculated in Fig. 8), in 2-week intervals between April and mid-August. Solid line: linear fit of time of maximum CI–CIII (Mcop) on temperature (T). Linear regression: $M_{cop} = 18.03 - 0.70 \times T$ ($R^2 = 0.56$, $P < 0.0001$). Lower panel: Time of CI–CIII maximum versus time of chlorophyll maximum (Mchl) in 2-week intervals. Stippled line indicates 1:1 correspondence. Solid line shows linear regression of Mcop on Mchl: $M_{cop} = 5.82 + 0.51 \times M_{chl}$ ($R^2 = 0.27$, $P = 0.03$). Stations at the Labrador Slope, Labrador east, West Greenland, Siglunes, Langes and Svinøy Arctic were excluded from linear regression analyses due to infrequent sampling.

¹ For identification of acronyms, see Fig. 4.

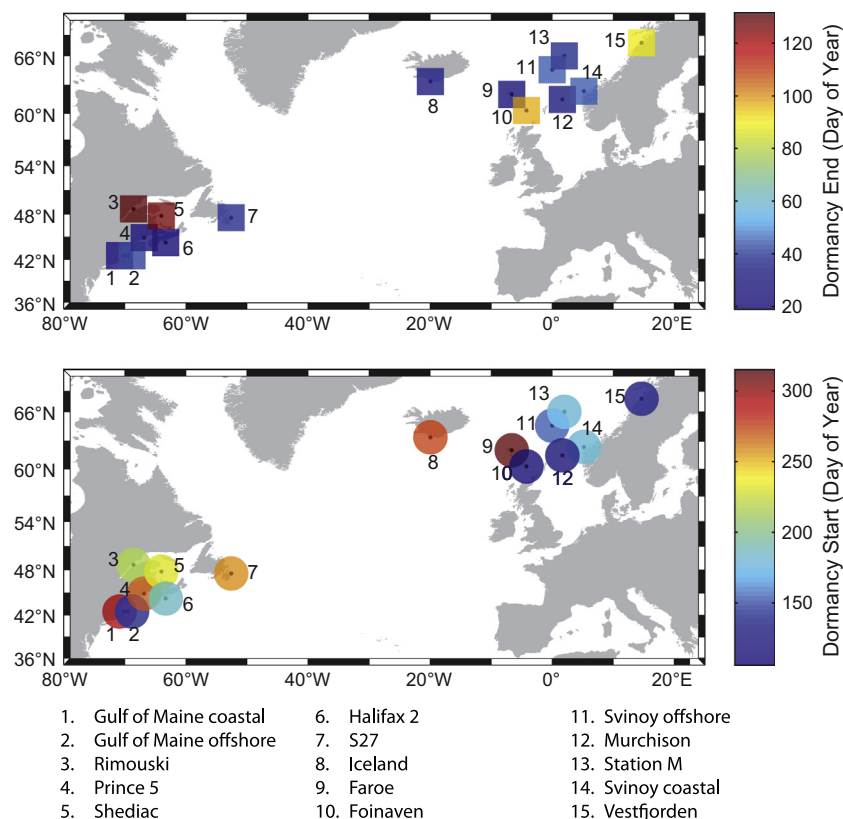


Fig. 10. Maps of the timing of dormancy exit (squares, upper panel) and entry (circles, lower panel) for *C. finmarchicus*. Symbol colour represents day of year, with the colour scale to the right of each panels. Data sources are described in Table 1 and in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Clutch size (eggs female⁻¹) increased with increasing prosome length in all regions and seasons, except in the WGBB region, where the two were not related. Most points fell below a line that has been suggested to define the upper limit to clutch size (CS_{max}) per unit length (Jónasdóttir et al., 2005; Fig. 12). One factor that contributes to variations in CS is food availability (Niehoff, 2004; Runge et al., 2006; Jónasdóttir et al., 2008; Head et al., 2013a). Runge et al. (2006) reported a linear relationship between CS and log transformed integrated chlorophyll concentration for females from the GB region. Plots of average experimental CS versus integrated chlorophyll concentration (Intchl) in other regions where the range of chlorophyll concentrations was large enough showed a rapid increase in CS at low chlorophyll concentrations, reaching an upper limit at high concentrations (Fig. 13). The degree of food limitation was investigated on a regional basis by comparing regional average values of CS/CS_{max} , using the Jónasdóttir et al. (2005) relationship to estimate CS_{max} , including data from all seasons, or from spring alone (Table 4). In spring, the average CS/CS_{max} values were correlated with average integrated chlorophyll concentrations across all regions ($P < 0.05$), if the anomalous WGBB region was omitted, although the highest CS/CS_{max} value (58% at RIM) was not in the region with the highest average chlorophyll concentration (ICE(N)). Despite the effect of chlorophyll concentration on CS, experimental averages for CS and PL were significantly correlated in the six of twelve regions (GB, SS, RIM, LS, ICE(S), NS), although not in the others.

Relationships between experimental spawning frequency and integrated chlorophyll concentration (Intchl) showed patterns similar to those shown for CS versus Intchl (Fig. 13), except in the WGBB. CS and SF were significantly correlated in most regions including the WGBB, the exceptions being ICE(S), NNWS and NS

(Fig. 14). As some of the scatter might have been due to the dependency of CS on female size, CS/CS_{max} values were plotted against SFs. The r^2 values for these relationships were generally slightly higher than those for CS vs. SF, and in the NS, the correlation between CS/CS_{max} and SF was significant ($r^2 = 0.12$) whereas the correlation between CS and SF was not (Fig. 14). Thus, females that are producing large clutches produce them more frequently and in most regions these increases seem to be related to increasing food intake, due to increasing chlorophyll concentration. In the WGBB region, however, the low spring temperatures may limit egg production, despite the high chlorophyll concentrations (Swailethorp et al., 2011; Kjellerup et al., 2012).

Egg production rates generally increased with integrated chlorophyll concentration to a saturating level (Figs. 15 and 16), showing patterns that resemble those for CS and SF vs. Intchl. Elsewhere (e.g. Runge et al., 2006; Head et al. 2013a) the relationship between EPR and Intchl has been fitted to an Ivlev function of the general form.

$$y = y_0 + a(1 - e^{-bx})$$

where y is the EPR at chlorophyll concentration x , y_0 is the EPR when the chlorophyll concentration is zero (for positive y_0 values), or indicates the threshold below which EPR is zero (for negative y_0 values), and a and b are constants. Since spring was the only season for which there were measurements in all regions, and in order to increase comparability among the datasets, only spring data were used to examine the relationship between EPR and integrated chlorophyll standing stock. The three parameter equation was fitted to all datasets, but in all regions a two parameter equation, where y_0 was equal to zero, gave an equally good fit to the data. There was

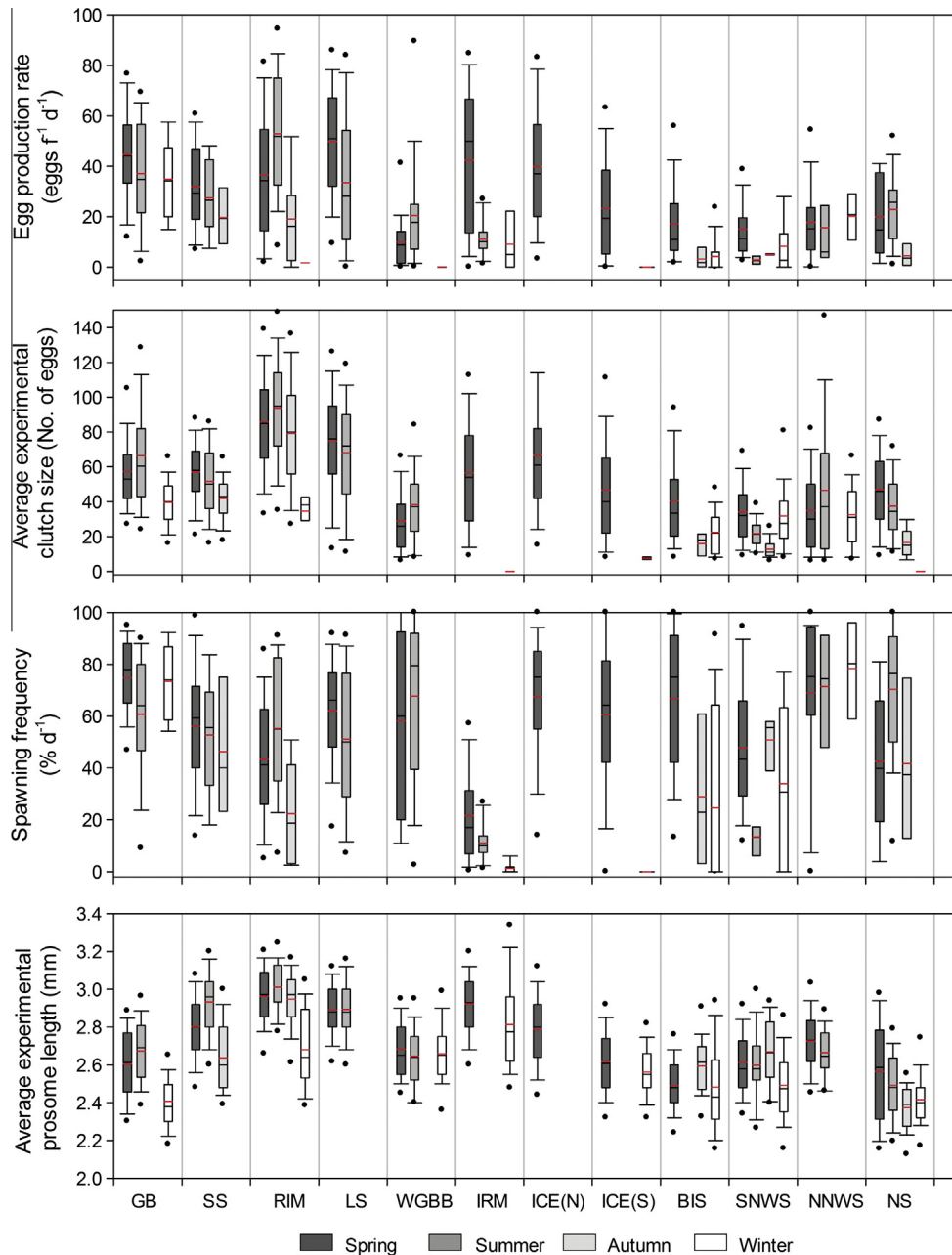


Fig. 11. Regional averages, by season, of *C. finmarchicus* egg production rates, clutch sizes, spawning frequencies and female prosome (body) lengths. Clutch sizes and prosome lengths were determined using experimental (i.e. station) averages. Horizontal lines, boxes, whiskers and points as in Fig. 4.

always a great deal of scatter about the Ivlev curves (Figs. 15 and 16, Table 5). The r^2 values for the Ivlev function were >0.2 in two of five regions in northwest Atlantic and in two of four regions in the northeast Atlantic, but <0.2 for all three regions in the central North Atlantic.

Two of the factors that might be expected to contribute to this scatter are female size and temperature. Female size has a direct effect via its influence on CS, and temperature could have either a direct effect, as it does on most physiological rates, or an indirect effect via its influence on female size, which varies with long-term food and temperature conditions (e.g. Campbell et al., 2001). A direct effect of temperature on spawning frequency has been demonstrated when groups of females from a common source population are brought into the laboratory and experimental incubations are run at different temperatures (Runge and Plourde, 1996; Hirche et al., 1997). In the sea, however, for Georges Bank

(January–June: Runge et al., 2006) and the NW Atlantic sub-polar gyre (January–June: Gislason, 2005; May–June: Head et al., 2013a) there was no observable effect. In order to see whether either of these factors was contributing to the variability in the expected EPR versus Intchl relationships, the residuals (i.e. the EPR values observed – the EPR values predicted by the Ivlev fits) were plotted against the average experimental female prosome length, or the ambient near-surface (and experimental) temperature within each region. In three regions (GB, RIM, LS) the residuals were positively correlated with prosome length, although the correlations were weak ($r^2 = 0.12$ – 0.20) (Table 6). Temperature was also positively correlated with the residuals in three regions (GB, RIM, ICE(N)), but in one (IRM) there was a negative correlation, and in all cases the proportion of the variance accounted for was low ($r^2 = 0.12$ – 0.21). Multiple regression analysis did not improve these results.

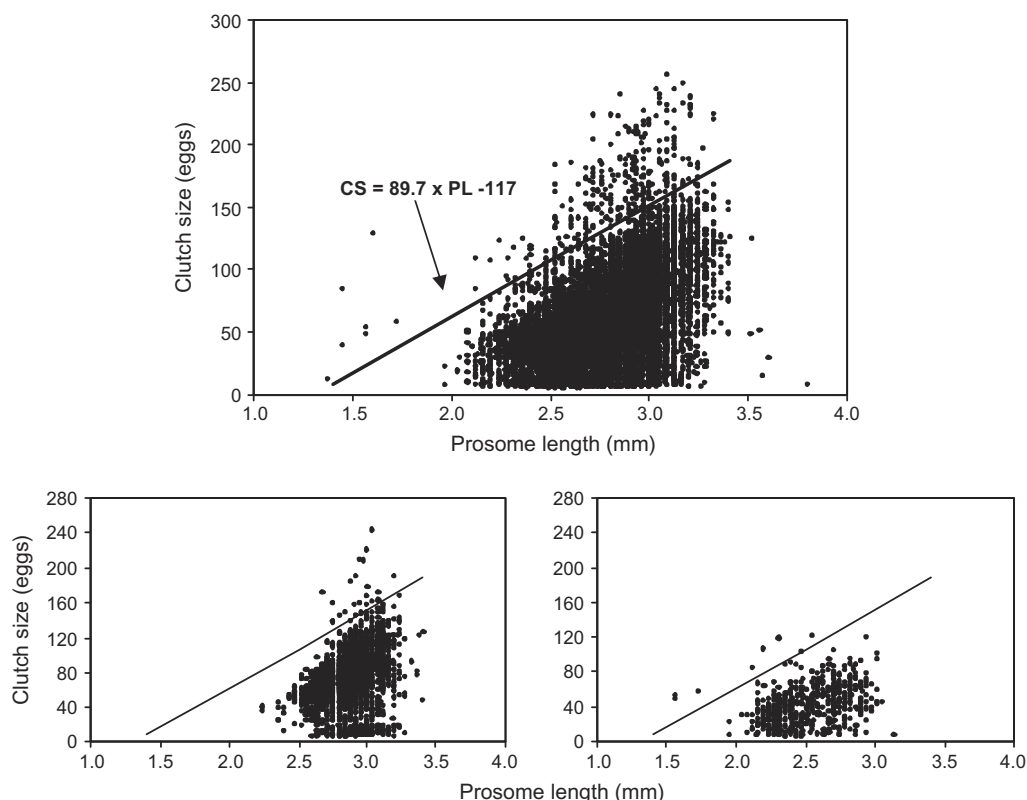


Fig. 12. Relationship between clutch size (CS) and female prosome length (PL) for all individuals from all seasons and all study regions of the North Atlantic (upper panel) and at two study regions, as examples, the Labrador Sea (LS, lower left panel) and the North Sea (NS, lower right panel). In all cases the line shows the clutch size upper limit for a given prosome length derived empirically by Jónasdóttir et al. (2005).

Even though temperature could not explain the scatter in the Ivlev plots, suggesting that it has no substantial impact on egg production rate in most regions in spring, the very low springtime temperatures in the WGBB region do appear to reduce EPRs since here, despite high chlorophyll concentrations, the upper limit for EPR was 11 eggs $\text{f}^{-1} \text{d}^{-1}$ (Table 5). As well, maximum EPRs measured during summer at higher temperatures were generally much higher than those found in spring at similar chlorophyll concentrations (Figs. 4 and 15).

Attempts were also made to reduce the scatter of the Ivlev plots by scaling the EPR values to female size. Both EPR/PL and EPR/ CS_{max} transformations were used, but neither led to any appreciable increases in r^2 values for the Ivlev curve fits. Elsewhere, EPR values have been scaled to female body size in terms of body carbon (C) or body nitrogen (N) content, and EPRs have been expressed as % female body C (or N) d^{-1} , using literature values for egg C and N content (Runge and Plourde, 1996). Runge et al. (2006) found that Ivlev curve fits to Intchl vs. EPR data, where the EPRs were expressed in this way, measured between January and June, tended to maximum values of 8.5% body C d^{-1} and 7.7% body N d^{-1} in the GB region. The r^2 value they report ($r^2 = 0.42$) was lower than the value reported here ($r^2 = 0.47$) for EPR expressed as eggs $\text{f}^{-1} \text{d}^{-1}$ derived using only data from April and May. Head et al. (2013a), using experimental data collected between May and July in the central basin of the Labrador Sea, found that scaling EPRs to female body N slightly increased the r^2 value for the Ivlev fit for EPR vs. Intchl ($r^2 = 0.48$ vs. 0.47), while scaling to body C reduced it ($r^2 = 0.38$). These curves tended towards maximum EPR values of 8.5% body C d^{-1} and 7.2% body N d^{-1} , very similar to the values on GB.

For a comparison of total *C. finmarchicus* egg production across regions, it should be noted that, despite variability in estimates of

individual female EPRs, total population egg production rates (eggs $\text{m}^{-2} \text{d}^{-1}$) are strongly influenced by the abundance of females, and that the contributions of the regions to the North Atlantic as a whole depend on their geographical areas. Thus, the gyres of the northeast (NNWS, SNWS) and the northwest (LS, IRM) Atlantic, with their high average female abundances and vast areas, account for >80% of the total North Atlantic egg production of *C. finmarchicus* on a daily basis in spring (Table 7). On the other hand, the duration of the spawning season is probably shorter for the gyres than in coastal or more southerly regions (see dormancy duration Fig. 10) and mortality rates for the egg–CI transition are also relatively high (see following section).

Mortality and survival of *Calanus finmarchicus*

There were significant differences in stage specific daily mortality rates among offshore and shelf habitats in the northeast and northwest Atlantic (Fig. 17a). Most notably, mortality from egg to CI was lower on the shelf than in the offshore in the northwest Atlantic (Kruskal–Wallis test, $p < 0.0001$), whereas CIV–CV mortality was significantly greater in shelf habitats than in both oceanic basins (Mann–Whitney test, $p < 0.05$). Mortality estimates for stages CV–CVI also showed important variability, but negative values, likely due to recruitment to and/or advection of adult stages from the overwintering CV stock on the shelf in the northeast Atlantic and offshore in the northwest Atlantic, precluded a more detailed analysis. No significant differences among habitats and regions (eastern vs. western North Atlantic) were detected for the stage pairs CI–CII and CIII–CIV ($p < 0.05$). Daily mortality rates for the egg–CI transition and the stage pairs CIV–CV and CV–CVI were positively related to temperature but with relatively low coefficients of dependence, the highest being for the egg–CI transition

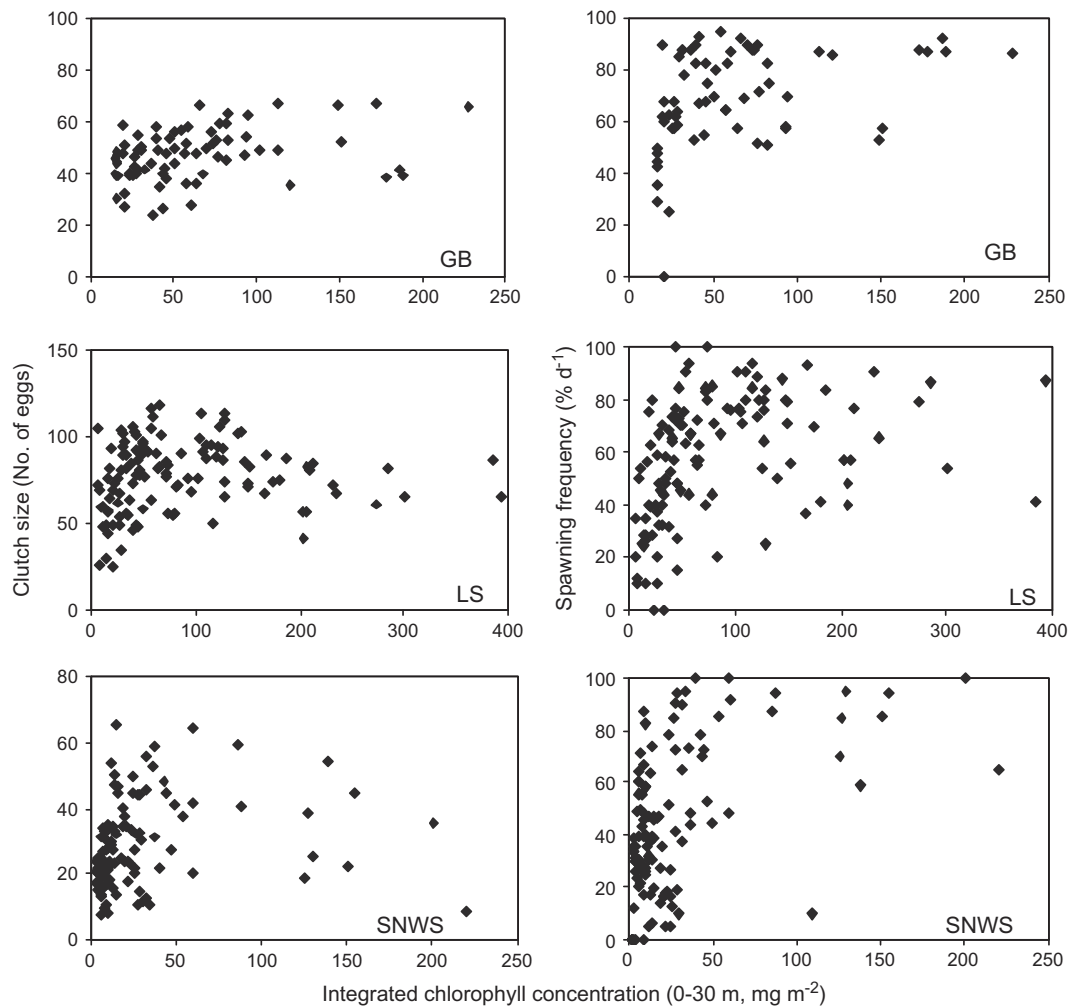


Fig. 13. Relationship between integrated chlorophyll concentration and experimental average clutch size (left column) or between integrated chlorophyll concentration and spawning frequency (right column) at three exemplary study regions in the North Atlantic.

Table 4

Average annual and spring relative clutch size CS/CS_{max} (see text). CS/CS_{max} for the WGBB region are averages for experiments run for 24 h, while the spring average chlorophyll concentration is the average over all spring experiments (24–43 h duration). Regions are as in Table 2.

Region	Annual average CS/CS_{max} (%)	Spring average CS/CS_{max} (%)	Spring average integrated chlorophyll (0–30 m, $mg\ m^{-2}$)
GB	48	46	79.6
SS	40	42	80.5
RIM	59	58	97.5
LS	51	53	80.2
WGBB	25	27	275.1
IRM	34	34	36.4
ICE(N)	50	50	136.7
ICE(S)	42	42	63.6
BIS	34	37	42.6
NNWS	28	28	32.9
SNWS	29	29	84.2
NS	40	43	53.2

($r^2 = 0.23$, Table 8). No significant relationship between mortality and temperature was detected in the other stage pairs (Table 8).

Because the proportion surviving through each stage pair represents the integration of daily mortality over stages, variations in survival among habitats and oceanic basins were somewhat

different from variations depicted for daily mortality rates (Fig. 17b). Survival from egg to CI was much greater for shelf than for offshore habitats on both sides of the Atlantic (habitats; M–W, $p < 0.0001$). Overall, differences in survival were significant until the CIII–CIV stage pair, but with a much lower significance level (Fig. 17b).

Average stage-specific recruitment rate (number $m^{-2}\ d^{-1}$) was calculated using the population birth rate (PopEPR) and the proportion surviving through each stage pair for the offshore and shelf habitats in the northwest and northeast Atlantic (Fig. 18). Region-specific survival trajectories of the developing cohort were normalised using the same PopEPR (50,000 eggs $m^{-2}\ d^{-1}$) for all regions. Survival trajectories were similar, with the notable exception of recruitment to CI offshore in the northwest Atlantic (low survival) and a low survival from CII to CIV in the offshore habitat in the northeast Atlantic.

Daily mortality rates for the egg–CI transition were generally higher in habitats colder than 6 °C where there was a greater likelihood for *C. finmarchicus* to co-occur with high abundances of its congeners *C. hyperboreus* and *C. glacialis* in the surface layer (Mann–Whitney test, $p < 0.0001$) (Fig. 19). These latter species are thought to feed on *C. finmarchicus* eggs and nauplii, since both reproduce before the spring bloom, so that their offspring are abundant and feeding during the bloom when *C. finmarchicus* are spawning. Our observations are consistent with this idea, since,

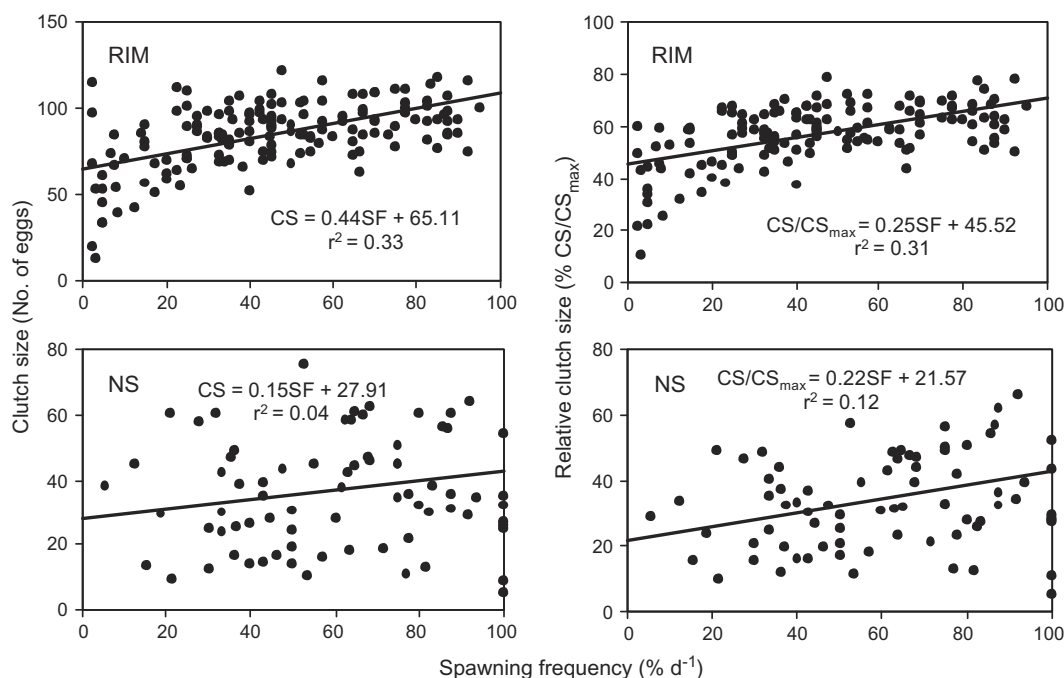


Fig. 14. Relationship between spawning frequency and clutch size (left column) or spawning frequency and relative clutch size (right column) at two exemplary study regions in the North Atlantic. The lines are the linear regressions, calculated excluding points where SF = 100%.

egg–CI survival was significantly reduced in cold waters (less than 1.5% of eggs surviving to CI), with 5–6 times lower survival success than in other warmer habitats (survival from egg to CI = 5.0–6.5%) (Mann–Whitney test, $p < 0.0001$).

Stage-specific daily mortality rates and survival through each stage pair were integrated into survival trajectories for each habitat (Fig. 20). For the same population EPR, lower survival from egg to CI (above) resulted in 5–6 times lower recruitment rate to CI in the colder (<6 °C) habitat, relative to other habitats. This large difference in survival during early stages development and recruitment to CI under the same temperature regime was reflected in the later stages as well, since overall the difference in recruitment to CI (survival during early stages) determined the recruitment rate to late development stages in all habitats.

To examine more systematically potential relationships between daily mortality rate in early stages (egg–CI) and environmental factors, we applied different multiple regression models to the data either from (1) regions based on the bathymetry (offshore, shelf) and large oceanic basins (northeast Atlantic, northwest Atlantic) or (2) thermal habitats (<6 °C, 6–11 °C, 11–16 °C) and potential abundance of *C. hyperboreus* and *C. glacialis* (high or low) (Table 9). In regions based on bathymetry and large oceanic basins, the multiple regression models were all significant and explained between 4% and 43% of the variability in egg–CI mortality, with higher levels of significance in the northwest Atlantic (20% and 43% in shelf and offshore regions respectively: Table 9A) than in the northeast. Temperature was significant on the shelf on both sides of the Atlantic, whereas egg–CI mortality was positively associated with CVIf abundance for shelf and offshore regions in the northwest Atlantic, but only marginally so in the offshore northeast Atlantic. The weakest levels of significance were given by the multiple regression model applied to the offshore northeast Atlantic (Table 9A). In regions determined using temperature conditions and potential abundance of *C. hyperboreus*/*C. glacialis*, the multiple regression models explained a greater proportion (27%) of the variability in egg–CI mortality in habitats with high abundances of Arctic *Calanus* species compared with those with low

abundance (Table 9B). Temperature and CVIf abundance were highly significant factors in habitats with high *C. hyperboreus*/*C. glacialis* abundance, while CVIf abundance had a much lower explanatory power for egg–CI mortality when the abundance of *C. hyperboreus*/*C. glacialis* was likely to be low.

Discussion

Abundance, distribution and life history characteristics of Calanus finmarchicus across its North Atlantic habitat

The data we have compiled here represent considerable multi-national effort spanning several decades. Much progress has been made in understanding *C. finmarchicus* life histories and the underlying processes needed to model its population dynamics in the context of developing climate change scenarios for the North Atlantic. The ocean circulation system and its associated water mass characteristics exert important influences on the distribution of *C. finmarchicus*, but distribution patterns are also influenced by regional differences in physiology, life history and ecological characteristics. Our analysis and synthesis of the assembled datasets focuses on regional similarities and differences between the northwest and northeast Atlantic with respect to processes determining the distributions and abundances of shelf and basin *C. finmarchicus* populations and life history responses to environmental variables.

The mean annual distribution of *C. finmarchicus* in the near surface layer, based on CPR measurements alone, is mainly restricted to the northern and western North Atlantic within an area delimited between the 5 °C and 10 °C annually-averaged sea surface isotherms (Fig. 5), in agreement with previous reports of mean annual maximal abundances at SSTs of between 5 and 10 °C, and critical SST boundaries of 9 and 12 °C (Beaugrand et al., 2008; Helaouët and Beaugrand, 2009). Overall, CPR data show that *C. finmarchicus* is more abundant in the northwest Atlantic, which is cooler and where the average chlorophyll standing stock is greater, than in the northeast Atlantic (see also Longhurst, 1998; Helaouët and Beaugrand, 2009; Helaouët et al., 2011). However, the results

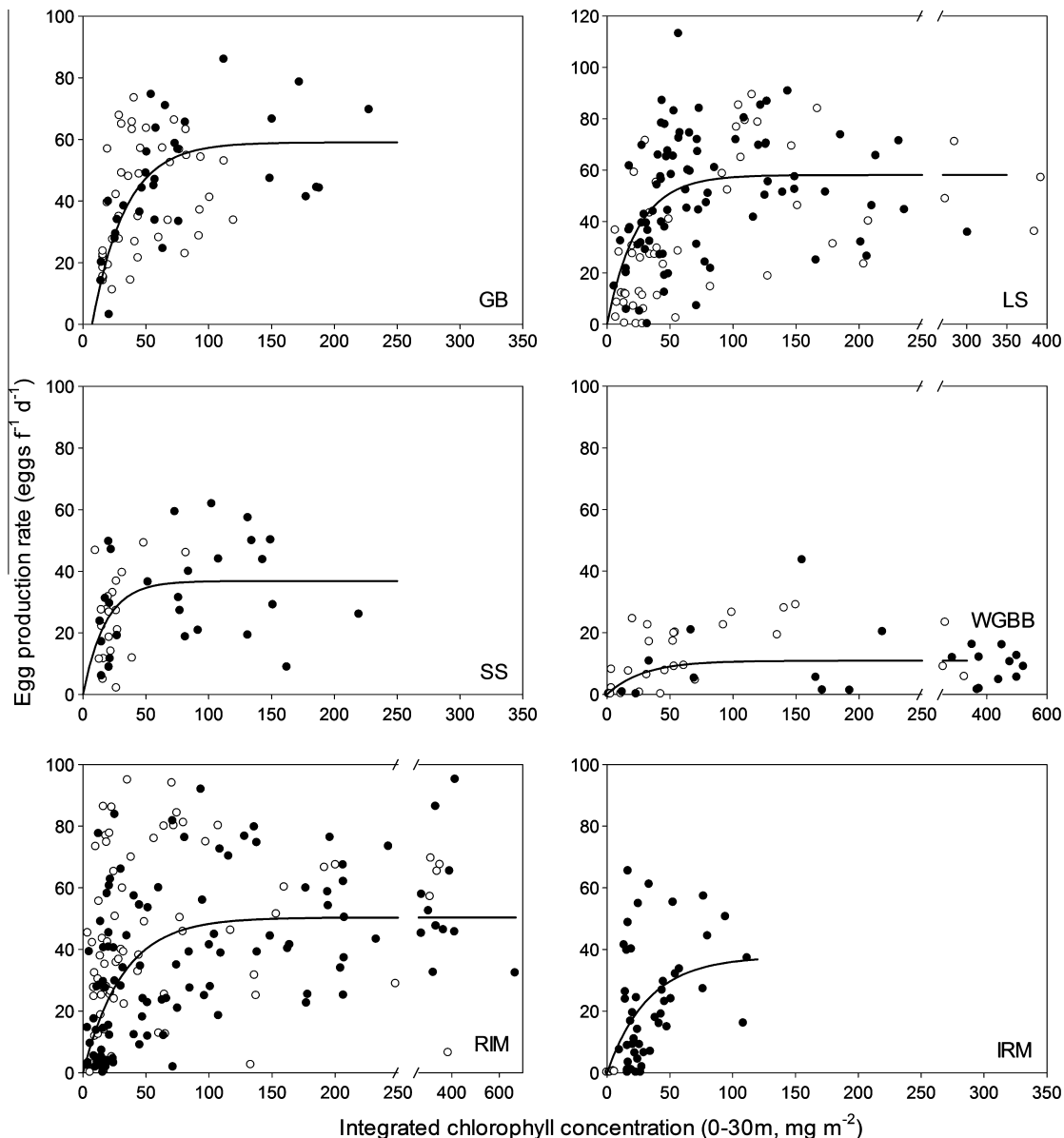


Fig. 15. Relationships between egg production rate and integrated chlorophyll concentration in the western study regions of the North Atlantic. Filled circles represent experiments carried out during spring; open circles show experiments carried out during other seasons. The curves show Ivlev functions fitted to the spring data, for which the parameters are given in Table 5. Experiments in the WGBB region were run for 24 h or longer (30–48 h). In all other regions experiments were run for 24 h.

(presented here as well as previously published observations), based on net data that includes the population epicentres within the subpolar-gyres of the Norwegian and Labrador Seas (Heath et al., 2000a, 2004, 2008; Head et al., 2003; Melle et al., 2004) indicate that the highest *C. finmarchicus* abundances are found north of the CPR routes. This supports the idea that maximum *C. finmarchicus* abundances are found in the deep basins of these seas (Fig. 6) or close to them. In the warm northeast Atlantic particularly, this changes our view of *C. finmarchicus* distribution compared to the perspective from CPR data alone. For this reason, since 2008, the spatial coverage of CPR monitoring has been expanded to cover the core areas of *C. finmarchicus* distribution in the Norwegian Sea. We analysed temperature measurements from the vertical domain of *C. finmarchicus* during the productive season and calculated mean maximum temperatures for the sampling sites (Fig. 8). Net data show that maximum abundances of *C. finmarchicus* in the core area of its distribution occur at sites with maximum temperatures between 11 °C and 13 °C. This is slightly higher than

previously reported values (Beaugrand et al., 2008; Helaouët and Beaugrand, 2009). To define the temperatures ranges that are presently occupied and those that are critical (i.e. beyond which *C. finmarchicus* is absent), further analysis that includes net collected data across the species distributional range is needed. Thus we conclude that habitat and population dynamics modeling in the future should include data sets obtained from CPR and net hauls, which complement each other in terms of sampling coverage.

The major overwintering areas for *C. finmarchicus* in the North Atlantic are the southern Norwegian Sea and the Irminger/Labrador Sea Sub-polar Gyre (Heath et al., 2004). The 24 net sampling sites included here in the analyses of demography and phenology are located at various distances from these two major overwintering epicentres (Table 1, Fig. 1b). Proximity to an overwintering centre has been suggested to be the main prerequisite for high abundance of *C. finmarchicus* (e.g. Heath et al., 2000a, 2008; Speirs et al., 2004; Torgersen and Huse, 2005; Head et al., 2013b) and to a large extent our observations are consistent with this

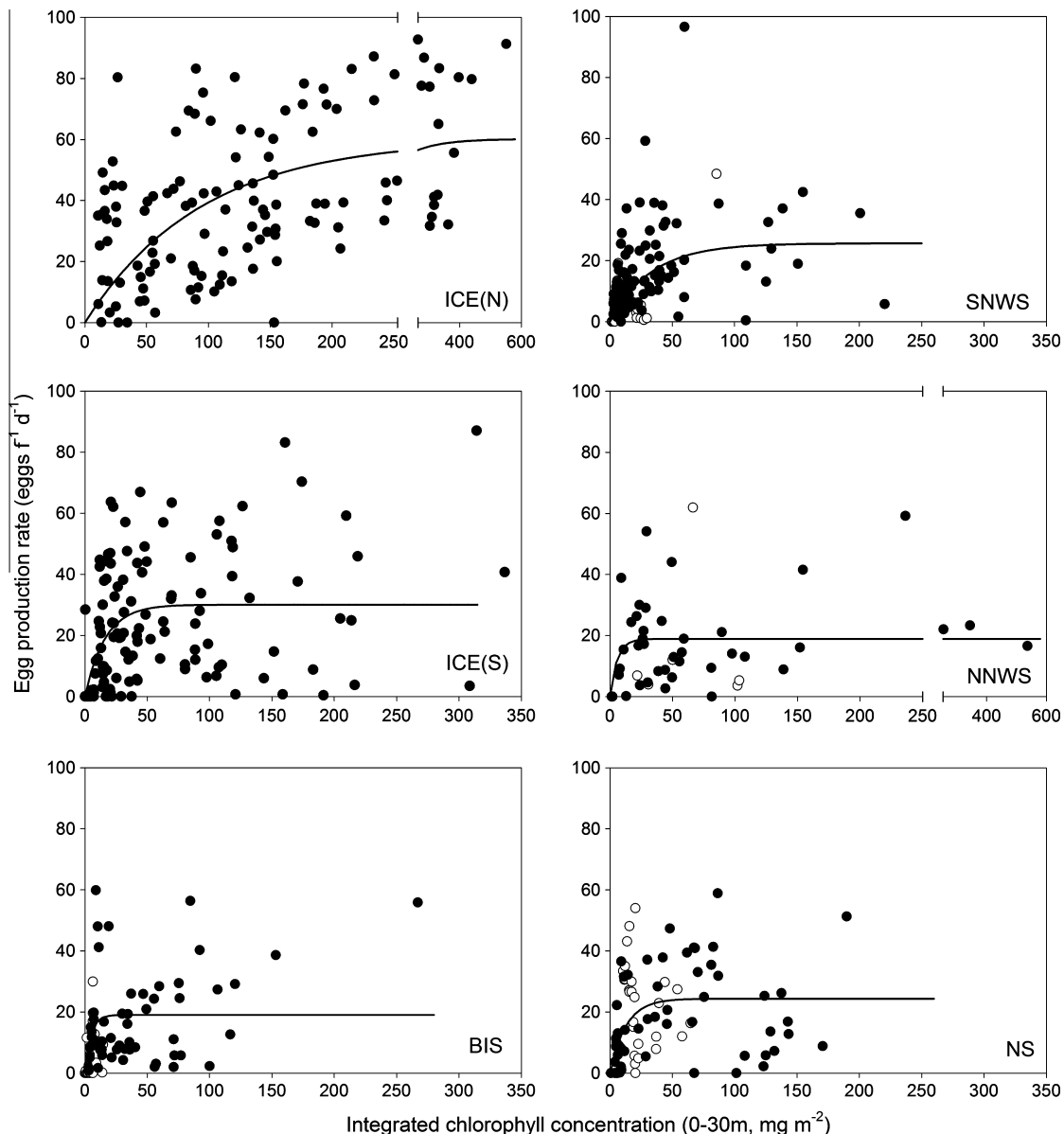


Fig. 16. Relationships between egg production rate and integrated chlorophyll concentration in the eastern study regions of the North Atlantic. Filled circles represent experiments carried out during spring; open circles show experiments carried out during other seasons. The curves show Ivlev functions fitted to the spring data, for which the parameters are given in Table 5. Experiments in all regions were run for 24 h.

notion, as the seven sites with highest abundances are located within or close to the two major overwintering basins (Fig. 6). Station Mike and the Svinøy section Atlantic and Arctic water regions are situated within the gyre of the southern Norwegian Sea. The Svinøy coastal region is located on the Norwegian Shelf, on the eastern rim of the southern Norwegian Sea deep basin, and coupled life-history/circulation models have demonstrated that *C. finmarchicus* can be recruited to the shelf population from the gyre population to the west (Speirs et al. 2004; Samuelson et al. 2009). Similarly, the Westmannaey site on the southern Icelandic shelf and the West Greenland shelf site on the southwestern Greenland shelf are situated close to the Irminger/Labrador Seas Gyre, while the Eastern Labrador Sea site is within the gyre. The overwintering female population at the central Labrador Sea site, also located within this gyre, is very abundant prior to spawning but here the number of first generation copepodites is very low, indicating high mortality during development and low local recruitment (Head et al., 2013a).

Total maximum abundance of *C. finmarchicus* populations at the study sites increased with increasing maximum water temperature within the range of about 3–13 °C, although some locations particularly in the North Sea, seem to deviate from this trend. Apart from being more distant from the overwintering epicentres these locations may also be less favourably positioned with respect to advection of animals from the population centres. The earliest recruitment to the young copepodite stages occurred at sites with high maximum temperatures, except at some coastal sites (Figs. 8 and 9 upper panel), and maximum abundance of the young stages occurred during or just after the phytoplankton bloom maximum (Fig. 9 lower panel). From these three relationships it is reasonable to infer that if recruitment can match an early phytoplankton bloom, production of *C. finmarchicus* populations will be improved. By contrast, *C. finmarchicus* in cold Arctic regions of the Norwegian Sea and in the northwest Atlantic tend to recruit to young stages long after the bloom and abundances of the species are lower there than in Atlantic water (Broms et al., 2009; Plourde et al. 2009b).

Table 5

Parameters for Ivlev functions ($y = a(1 - e^{(-bx\text{Intchl})})$) relating egg production rate (EPR: y) and 0–30 m integrated chlorophyll concentration (Intchl), estimates of integrated chlorophyll concentrations (Intchl 95%) required to reach 95% of EPR_{max} (a), average regional chlorophyll concentrations in spring (Avg. Intchl) and the percentage of experimental stations in spring where the chlorophyll concentration exceeded Intchl 95% (No. of stns.). For the WGBB region results from all experiments (24–48 h duration) were used. Regions are as in Table 2.

Region	a	b	r^2	Intchl 95% (mg m ⁻²)	Avg. Intchl in spring (mg m ⁻²)	No. of stns >Intchl 95% (%)
GB	60.4	0.029	0.47	103.3	79.6	25
SS	36.8	0.056	0.15	53.3	80.5	63
RIM	50.3	0.032	0.26	93.6	97.5	33
LS	58.1	0.042	0.19	71.9	80.2	39
WGBB	10.9	0.035	0.07	85.5	275.1	76
IRM	35.0	0.033	0.08	90.8	36.4	8
ICE(N)	60.1	0.011	0.18	282.6	136.7	11
ICE(S)	30.1	0.062	0.13	48.6	55.1	39
BIS	19.0	0.215	0.05	13.9	42.6	63
SNWS	25.6	0.052	0.23	57.4	32.9	14
NNWS	18.9	0.174	0.08	17.2	84.2	85
NS	24.4	0.078	0.24	38.2	53.2	49

Table 6

Correlations among residuals (observed EPR – predicted EPR) from the Ivlev plots of EPR versus Intchl with either *in situ* near-surface temperature (T) or prosome length (PL), and between T and PL. Only results for correlations with $P < 0.05$ are shown. Regions are as in Table 2.

Region	Residuals vs. T (Sign, r^2)	Residuals vs. PL (Sign, r^2)	PL vs. T (Sign, r^2)
GB		+, 0.20	+, 0.23
SS			+, 0.17
RIM	+, 0.12	+, 0.12	+, 0.27
LS	+, 0.21	+, 0.13	+, 0.22
WGBB			
IRM	–, 0.15		
ICE(N)	+, 0.18		
ICE(S)			
BIS			
SNWS			–, 0.12
NNWS			–, 0.14
NS			+, 0.24

Table 7

Springtime average egg production rates (EPR: eggs female⁻¹d⁻¹), female abundances, regional areas and estimates of contribution of each region to *Calanus finmarchicus* egg production in the North Atlantic.

Region	EPR (eggs f ⁻¹ d ⁻¹)	Female abundance (f m ⁻²)	Area of region (x 10 ¹⁰ m ²)	Regional EPR (x 10 ¹⁴ eggs d ⁻¹)
GB	44.6	1130	5.7	29
SS	32.0	1207	11.3	44
RIM	36.6	1280	23.6	111
LS	51.8	5522	94.7	2709
WGBB	9.9	3075	10.3*	31
IRM	18.9	2963	95.5	535
ICE(N)	39.9	2743	23.1	253
ICE(S)	31.0	1073	27.1	90
BIS	17.2	1302	30.7	69
SNWS	15.1	1833	21.0	58
NNWS	17.8	4608	91.0	746
NS	19.9	289	23.9	13

* Area for WGBB includes only the southern part of Baffin Bay, as Disko Bay is thought to be the northern limit of *C. finmarchicus* distribution. Regions are as in Table 2.

Neither high temperatures nor recruitment during early phytoplankton blooms are enough to guarantee an abundant population, since some sites are characterised by high temperature and agreement between recruitment and bloom time but yet have

scarce populations. One explanation that we have not explored by data analysis here is unevenly distributed predation pressure among the sites. In the Norwegian Sea a range of different predators have been identified and both direct and circumstantial evidence of predation have been given. Predation from herring on copepods which were mainly *C. finmarchicus*, was estimated to be similar to the annual production of the prey (Dommasnes et al. 2004), Skjoldal et al. (2004) estimated pelagic fish predation on *Calanus* to be ~30% of annual production, Utne et al. (2012) using ecosystem model simulations estimated predation from pelagic fish stocks at 35 mill tonnes, or 18% of the annual *C. finmarchicus* production (Hjollo et al., 2012). It has also been found that *C. finmarchicus* stock size is negatively correlated to total pelagic fish stock size the previous year in the Norwegian Sea (Olsen et al., 2007; Huse et al., 2012), suggesting top down controls at a large scale. Additionally, predation from macroplankton predators and mesopelagic fishes may greatly exceed predation from the pelagic fish stock (Skjoldal et al., 2004). In fact, when summing assumed consumption of *C. finmarchicus* by all the predators the total predation loss tends to be much larger than the *C. finmarchicus* production in the Norwegian Sea, strongly suggesting that predation is the terminal cause of mortality there and that new estimates on production and consumption are needed. We do not have similar information on *C. finmarchicus* predators in the other deep basins, but the presence of large pelagic fish stocks in the Norwegian Sea is one clear difference in the predatory communities between the two major overwintering deep basins in the Norwegian Sea and the Labrador/Irminger Seas. However, even though *C. finmarchicus* may be more heavily grazed in the Norwegian Sea, this is also the basin with the highest *C. finmarchicus* abundance. Therefore, we hypothesise that the Labrador and Irminger Sea possess predatory stocks made up of macrozooplankton and mesopelagic fishes that inflict considerable predation pressure on *C. finmarchicus*.

Predation on the overwintering population is another source of mortality that needs further investigation, although data from the two major overwintering basins, the southern Norwegian Sea and the Labrador Sea, indicate that mortality during overwintering is low and less variable than during the active phase (Head et al., 2013a; Melle et al., in prep). Still, losses of almost the entire population from the Norwegian shelf during winter indicate that predatory or advective losses during winter may be substantial in shallower regions (Slagstad and Tande, 1996; Melle et al., 2004).

Predation may shape the population distribution in the regions of marginal *C. finmarchicus* productivity such as the sites with low temperature or with a mismatch to the bloom. Our mortality rate calculations suggest high predation pressure on eggs and nauplii, which we suggest is by the suspension feeders, *C. hyperboreus* and *C. glacialis* (in addition to cannibalism by *C. finmarchicus* CVIf). This occurs because *C. hyperboreus* and *C. glacialis* have multi-year life cycles and therefore are present as copepodite stages early in the spring bloom, when *C. finmarchicus* reproduction is starting (Conover, 1988). Thus, during the late spring-early summer period, recruitment of *C. finmarchicus* is suppressed and there is a delay in the timing of maximum CI–CIII abundance until well after the bloom (section ‘Mortality and survival of *Calanus finmarchicus*’, Figs. 19 and 20). This interaction with Arctic congeners should be more prominent at sites where CI–CIII recruits peak several weeks after the bloom, such as at the Anticosti Gyre, Gaspé Current, Station 27 and Labrador Shelf sites. One exception is the lower St. Lawrence estuary (RIM) where the bloom is delayed relative to the adjacent Anticosti Gyre due to freshwater runoff, so that it co-occurs with the relatively late CI–III peak (Fig. 9). Surface layer temperatures in cold (3 °C mean) and warmer habitats (10 °C mean) during the population growth period should result in development times from egg to N6 of 30 and 15 days respectively,

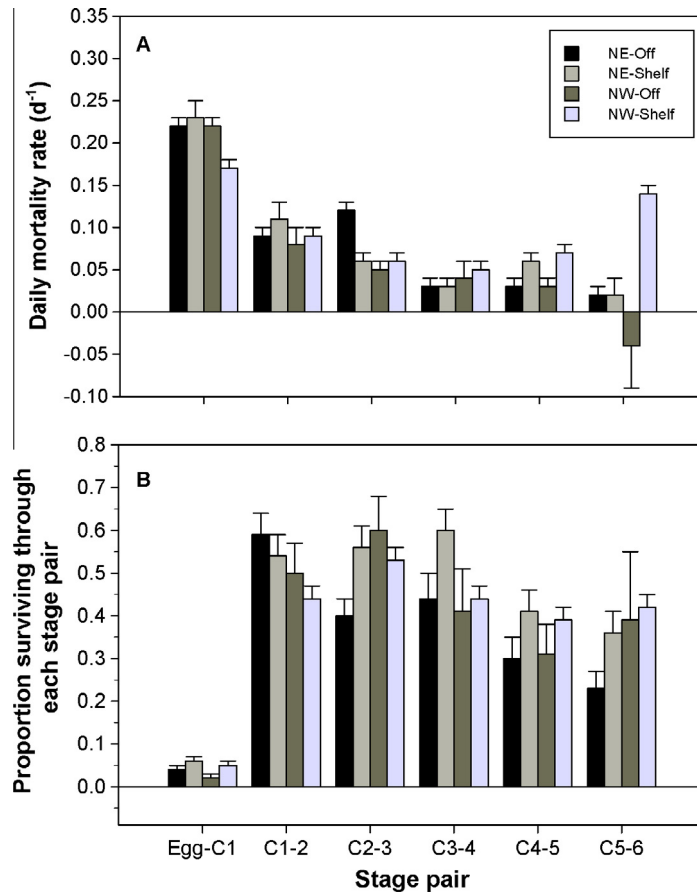


Fig. 17. (A) Stage-specific daily mortality rates and (B) proportion surviving through each stage pairs during population growth period of *C. finmarchicus* in offshore and shelf habitats in the northeast (NE) and northwest (NW) Atlantic. See text for definition of different habitats. Values represent the mean \pm standard error.

Table 8

Stage-specific coefficients, significance, and r^2 of the relationship between estimated daily mortality rates and surface layer temperature during *C. finmarchicus* population growth period. Data were fitted by non-linear least-squares to the equation $m = ae^{bt}$, where m is the estimated mortality and T the surface layer temperature.

Stage pair	r^2	p -value	a	b
Egg–C1	0.227	<0.0001	0.101	0.094
C1–C2	–	>0.05	–	–
C2–C3	–	>0.05	–	–
C3–C4	–	>0.05	–	–
C4–C5	0.041	<0.0001	0.034	0.090
C5–C6	0.048	<0.0001	0.044	0.098

representing only a two week difference (Campbell et al., 2001). Therefore, differences in temperature alone cannot explain the long delays (up to 3.5 months) observed between the timing of maximum in C1–C3 abundance and the bloom at the cold water sites, which is consistent with our suggestion of predation by the arctic *Calanus* species.

The demographic pattern observed in the central Labrador Sea is similar to the spatial demography observed within the central Irminger Basin, for which sources of overwintering copepodites are hypothesised to be recruitment along the eastern and northern margins and subsurface horizontal transport from the east Greenland slope and Labrador Sea (Heath et al., 2008). Recruitment failure in the central Irminger Basin, likely due to high predation mortality in the early life stages and/or starvation of the first feeding nauplii at persistently low food conditions, is hypothesised to preclude direct descent as a major source of overwintering stage CV (Heath et al., 2008). In the central Labrador Sea, food (i.e.

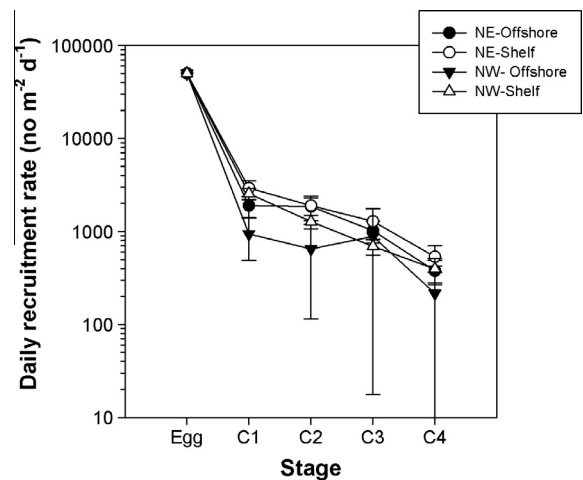


Fig. 18. Stage-specific daily recruitment rate during population growth period of *C. finmarchicus* in offshore and shelf habitats in the northeast (NE) and northwest (NW) Atlantic. See text for definition of different habitats. Values represent the mean \pm standard error.

phytoplankton) concentrations and egg production rates are higher (e.g. Fig. 15) than in the Irminger Basin, and early life stage mortality due to cannibalism by adult *C. finmarchicus* and predation by *C. hyperboreus* and other as yet unrecognised predators (Head et al., 2003, 2013a) may be more important sources of recruitment failure.

The deep basin populations appear to be the main sources of supply of *C. finmarchicus* overwintering stages to the central and

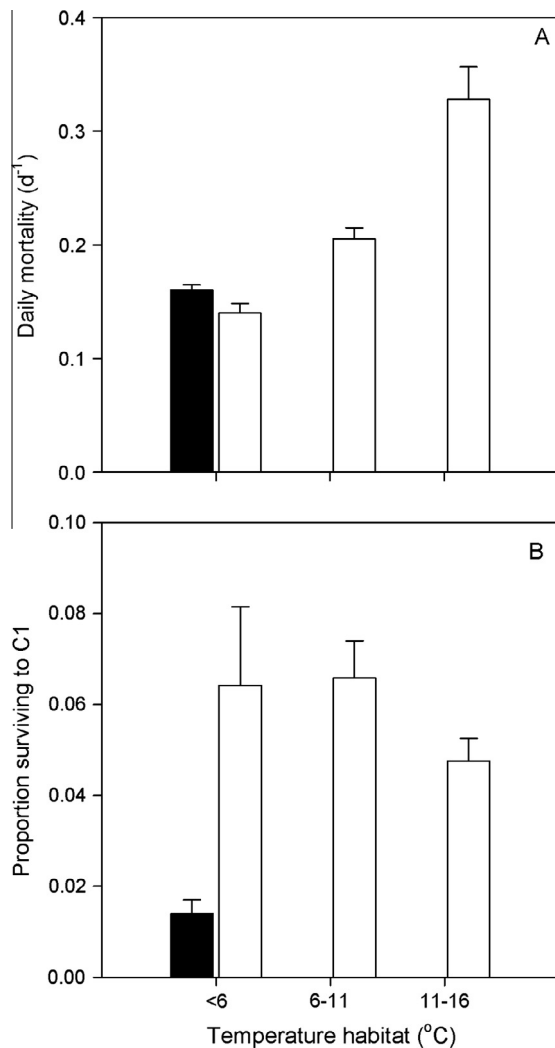


Fig. 19. Daily mortality rates in stage pair egg–C1 (A) and proportion surviving to C1 (B) during the population growth period of *C. finmarchicus* in temperature habitats with high (black) or low (white) probable elevated abundance of *C. hyperboreus* and *C. glacialis*. See text for definition of different habitats. Values represent the mean \pm standard error.

northeastern North Atlantic shelf populations. On-shelf transport from the Norwegian Basin of overwintered adults prior to mid-summer and early life stages later in the year is the primary source of *C. finmarchicus* to the relatively narrow Norwegian shelf (Samuelson et al., 2009). Field and modelling studies (e.g. Heath et al., 1999; Harms et al., 2000) support the hypothesis that the population of *C. finmarchicus* in the North Sea is sustained by annual spring advection of late-stage individuals originating from high concentrations of stage CVs overwintering in the deep Atlantic and Norwegian Sea, particularly the Faroe-Shetland Channel (Heath et al., 1999). In the North Sea, the maximum abundance of *C. finmarchicus* is low (on the order of 5×10^3 ind. m⁻²; Heath et al., 2000a; Jónasdóttir and Koski, 2011), despite relatively high egg production rates (Jónasdóttir and Koski, 2011; Fig. 16). The primary factor controlling abundance in the North Sea appears to be predation mortality during the early life stages (Jónasdóttir and Koski, 2011), which probably also holds for the older stages, which cannot migrate vertically far enough to avoid predation, because of the relatively shallow bathymetry.

Other time series sites are farther from the deep basin epicentres or have lesser degrees of direct advective connection, which limits repopulation from the deep ocean overwintering sites by

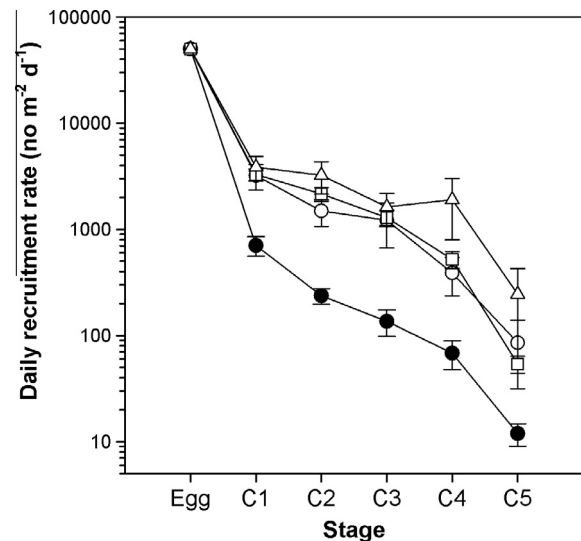


Fig. 20. Stage-specific daily recruitment rate during population growth period of *C. finmarchicus* in thermal habitats < 6 °C (circles), 6–11 °C (squares), 11–16 °C (triangles) with high (black) or low (white) probable abundance of *C. hyperboreus* and *C. glacialis*. See text for definition of different habitats. Values represent the mean \pm standard error.

members of the overwintering or first generations. The Arendal and the two northern Icelandic sites have long transport routes from their nearest overwintering areas, the Norwegian Sea and the deep basins south of Iceland (Gislason and Astthorsson, 1998; Heath et al., 2000b; Astthorsson and Gislason, 2003; See Appendix and Fig. 1b), and the Faroese Shelf site is located behind a strong tidal front, within an anticyclonic shelf gyre that results in a short retention time and increased dispersal of shelf plankton and reduced advection of oceanic plankton onto the shelf (Debes and Eliassen, 2006). Recruitment of G0/G1 on the Labrador/Newfoundland shelves that are adjacent to a deep overwintering area does not seem to be as effective as the recruitment to the southern Icelandic and western Norwegian shelves (Westmannaeyj and Svinøy Coast sites). This may be because the Labrador/Newfoundland shelves are broad relative to the Icelandic/Norwegian shelves and are not deep enough to sustain overwintering populations, and also because there are relatively high concentrations of *C. hyperboreus* and *C. glacialis* present in spring, which can consume *C. finmarchicus* eggs and nauplii (see sections 'Mortality and survival of *Calanus finmarchicus*' and 'Mortality').

In contrast to the northeast Atlantic, the marginal seas of the northwest Atlantic (the Gulf of St. Lawrence and the Gulf of Maine) harbour local overwintering stocks, and local production is as important as advective supply from the slope water in sustaining local *C. finmarchicus* populations. Overwintering stage CVs reside at 150–175 m in the deep (300–400 m) Laurentian Channel of the Gulf of St. Lawrence and the deep basins (250–400 m) of the Gulf of Maine (Plourde et al., 2001; Johnson et al., 2008) at abundances ($20\text{--}40 \times 10^3$ ind. m⁻²) of the same order of magnitude as *C. finmarchicus* stocks in the deep basins (e.g. Heath et al., 2000b; Halvorsen et al., 2003). As well, a modeling investigation has indicated that the Gulf of St. Lawrence population is self-sustaining (Zakardjian et al., 2003). The roles of local production versus advective supply from the Scotian Shelf, Labrador and Atlantic slope water in maintaining the Gulf of Maine basin populations are still not determined, although there is evidence that coastal Gulf of Maine production is a significant local source (Maps et al., 2012). Nevertheless, the relatively warm overwintering temperatures in the deep Gulf of Maine reduce dormancy duration, and supply from the colder northern sources in the Gulf of St. Lawrence and

Table 9

Calanus finmarchicus mortality and environment. Statistics of the linear multiple regression models of mortality in egg–CI against temperature, chlorophyll a biomass and adult female copepod abundance in different habitats. Habitats were: (A) offshore/shelf regions in the northeast (NeATL) and northwest (NwATL) Atlantic or (B) probability that congeners *C. hyperboreus* and *C. glacialis* occur in high abundance in the surface layer based on literature results (see text). Analyses were performed with ln-transformed data.

	Independent variable: mortality egg–CI							
	Off-NeATL		Shelf-NeATL		Off-NwATL		Shelf-NwATL	
	Partial Corr. Coeff.	<i>p</i>	Partial Corr. Coeff.	<i>p</i>	Partial Corr. Coeff.	<i>p</i>	Partial Corr. Coeff.	<i>p</i>
(A) Habitats in NeATL and NwATL								
Intercept	0.730	<0.0001	0.630	<0.0001	0.51	<0.0001	0.600	<0.0001
Temperature	0.020	>0.05	0.050	<0.01	0.04	>0.05	0.050	<0.0001
Chlorophyll a	–0.010	>0.05	0.010	>0.05	–0.01	>0.05	–0.001	>0.05
Abundance CCVif	0.010	<0.05	0.0003	>0.05	0.03	<0.0001	0.010	<0.01
<i>r</i> ² adjusted	0.04		0.09		0.43		0.20	
<i>p</i>	<0.05		<0.01		<0.0001		<0.0001	
(B) High/low <i>C. hyperboreus</i>/<i>C. glacialis</i> habitats								
	High		Low					
	Partial Corr. Coeff.	<i>p</i>	Partial Corr. Coeff.	<i>p</i>				
Intercept	0.670	<0.0001	0.610	<0.0001				
Temperature	0.020	<0.0001	0.060	<0.0001				
Chlorophyll a	–0.004	>0.05	–0.004	>0.05				
Abundance CCVif	0.010	<0.0001	0.010	<0.01				
<i>r</i> ² adjusted	0.27		0.14					
<i>p</i>	<0.0001		<0.0001					

distant Labrador Sea may become increasingly important to maintain the population of *C. finmarchicus* in the Gulf of Maine region under climate forcing.

When considering impacts of climate warming on *C. finmarchicus* distribution in the northern North Atlantic, the differences in the interplay between bathymetry, advective supply and local birth and mortality rates all need to be taken into account. Increasing surface layer temperature will certainly be a factor at the southern geographical edge of the species range. Surprisingly, the upper temperature threshold at which growth and development rates start to be constrained is not well known, but is likely to be between 16 and 19 °C (Møller et al., 2012; Runge and Preziosi, unpubl. observations). Overwintering water temperature is also a factor for southern populations; for example, the warm deep water temperatures in the Gulf of Maine currently appear to force *C. finmarchicus* to emerge from diapause considerably earlier than it does in more northern regions (Saumweber and Durbin, 2006; Johnson et al., 2008; Maps et al., 2010, 2012), an effect that is likely to be exacerbated as water temperatures warm in the future. At the moment the southern limit of the distribution of *C. finmarchicus* in the northwest Atlantic (the Gulf of Maine/Georges Bank) is maintained by the stocks overwintering in the basins in the Gulf of Maine (Miller et al., 1998) and along the shelf-slope region of the Scotian Shelf (Head et al., 1999; Head and Pepin, 2008), in combination with advection from upstream sources, including the surface layers of the Scotian Shelf and the Gulf of St. Lawrence (Head et al., 1999) and the Labrador Sea, via the Labrador Shelf and Slope water currents (Greene and Pershing, 2007; Head and Pepin, 2010). In the northeast Atlantic, however, the mean residual flow is from south to north, resulting in warmer water incursions at higher latitudes. Maintenance of *C. finmarchicus* on the northeast shelves will therefore depend on continuing advective supply from the deep Norwegian Sea. For the North Sea, the southern edge of the northeast Atlantic shelf distribution, advective supply is a function of the deep transport of *C. finmarchicus* from the Norwegian Sea to the Faroe-Shetland Channel, together with local and regional wind fields transporting individuals into the North Sea in the surface layers. The distribution of *C. finmarchicus* at its northern boundary and its ability to colonise the Arctic may be constrained by the effects of less light and colder temperatures, which lead to both a shorter phytoplankton growth season length and slower *C. finmarchicus* development rates (Broms and Melle, 2007; Broms et al., 2009; Ji et al., 2012). As well there is the potential for predation on *C. finmarchicus* early life stages by its Arctic congeners, *C. glacialis* and *C. hyperboreus*.

Climate change scenarios can be investigated in coupled physical-life history models for shelf and offshore regions of both the northeast and northwest Atlantic, although accurate prediction of future distributions will also require information on the distributions of potential predators and how they respond to climate change.

Life history responses to environmental variables

Understanding the spatial population dynamics of *C. finmarchicus*, or any animal population in the sea, requires the capability to quantitatively characterise birth and mortality rates, as well as immigration and emigration rates. The representation of copepod life histories, including population demographics, by life history models has been discussed elsewhere (e.g. Runge et al., 2005; Ji et al., 2010; Neuheimer et al., 2010; see also section below). Essential to this quantitative analysis is the parameterization of vital rates, including development, growth, egg production and mortality. While models of *C. finmarchicus* life cycles have already shown insight into factors controlling populations at both regional (e.g. Speirs et al., 2004; Samuelson et al., 2009; Maps et al., 2012) and basin scales (e.g. Speirs et al., 2006; Hjøllø et al. 2012), the choice of parameter values in many cases is still open to considerable uncertainty (e.g. Maps et al., 2012) due to the need for more comprehensive datasets. For example, the parameterization of growth rates as functions of food availability and temperature is based almost exclusively on the now classic work by Campbell et al. (2001) using *C. finmarchicus* collected from the Gulf of Maine in the northwest Atlantic. The extent to which the physiological responses of *C. finmarchicus* captured from the northwest Atlantic are representative of those of individuals in the northeast Atlantic is still an open question in light of the finding of genetic differentiation of two and perhaps as many as four populations across the species' range (Unal and Bucklin 2010). Here we interpret the available data on diapause timing, egg production and mortality rates in relation to habitat variables in order to assess the state of our understanding of parameterization of these variables across the entire basin.

Diapause duration and timing

Our analysis of the pan-Atlantic demographic data (Figs. A1–A6) provides evidence for a longer active period and shorter dormancy

duration in the northwest Atlantic than in the northeast, although not necessarily for a greater number of distinct “generations”. An interpretation consistent with the finding of higher chlorophyll concentrations and lower surface temperatures in the northwest Atlantic is that the more favourable food conditions contribute to more sustained egg laying, leading to a prolonged growth season, but combined with slower development this do not necessarily result in more generations. For example, at the Gulf of St. Lawrence Rimouski station, prolonged summer production results in a broad period of recruitment lasting several months. Seasonally late egg production in the northwest Atlantic may, however, also yield an active population of early copepodites constituting a “lost generation”, i.e., individuals that do not enter dormancy with the bulk of the population and consequently delay the metric indicating start of diapause. The presence of a fraction of the population that continues to develop while most of the population enters dormancy has been observed in many locations (e.g., Meise and O'Reilly, 1996), although the offspring of these individuals may not survive to reproduce. Higher overwintering temperatures in the northwest Atlantic, where overwintering *C. finmarchicus* experience temperatures ranging from about 1 to 10 °C, with highest values in Emerald Basin on the Scotian Shelf (Head and Pepin, 2008) and in the Gulf of Maine (Maps et al., 2012), likely also contribute to differences in dormancy timing and duration.

There is variability in the number of identifiable generations among sampling sites, but without any distinct west–east pattern (Fig. A1–A6). In the coastal Gulf of Maine stage CV emerges from dormancy in late December, possibly earlier (Durbin et al., 1997; Maps et al., 2012), and 2–3 generations are produced over the course of a season. In contrast, upstream of the Gulf of Maine on the Scotian Shelf, emergence occurs in February–March and 1–2 generations are produced (Sameoto and Herman, 1990; Herman et al., 1991; McLaren et al., 2001), although production may extend into the fall in some areas and some years (Head and Pepin, 2008). In the adjacent slope water, emergence from dormancy also occurs in February–March, but yields only one generation (Miller et al., 1991). In the Gulf of St. Lawrence and on the Newfoundland Shelf, *C. finmarchicus* generally emerges from diapause in late March–early April and produces one large summer generation followed by a smaller one in autumn (Plourde et al., 2001; Johnson et al., 2008; Pepin et al., 2011). In the Iceland Basin, stage CVs emerge in March–April, while in the Irminger Basin, emergence begins in February (Gislason and Astthorsson, 2000). In the Irminger Basin, *C. finmarchicus* mainly produces one generation before entering diapause in late July or early August, but a small percentage molt to adulthood and continue active development (Heath et al., 2008). On the shelf south of Iceland, 2–3 generations are produced, with the main population peaks in May/June and June/July (Gislason et al., 2000). In the Norwegian Sea, *C. finmarchicus* start to emerge from dormancy in January and February (Melle et al., 2004; Edvardsen et al., 2006), and there are typically one or two generations annually (Petersen et al., 2000; Melle et al., 2004; Broms and Melle, 2007; Broms et al., 2009; Bagoeien et al., 2012).

A qualitative assessment finds the demographic data consistent with a lipid dependent mechanism (Irigoin, 2004; Johnson et al., 2008; Maps et al., 2010, 2012) to explain spatial and temporal variability in dormancy timing and duration. Under this hypothesis, the food and temperature conditions determine the accumulation of storage lipid in individual copepodites. Only when lipid accumulates above a nominal threshold level is the signal (likely hormonal, see Tarrant et al., 2008) given for that individual to prepare for diapause in stage CV. During lipid accumulation, *C. finmarchicus* has been shown to regulate the composition of the storage lipids, biochemically altering the saturation state (Clark et al., 2012). If the threshold is not attained and hence the signal not received, the individual remains active and molts to adulthood. According

to this hypothesis, duration of dormancy is determined by the rate of storage lipid utilisation, which is regulated by storage lipid composition (Clark et al., 2012) and is temperature dependent (Saumweber and Durbin, 2006; Pierson et al., 2013). Thus, the within-region and cross Atlantic differences in dormancy timing and duration could reflect the environmental conditions experienced by individuals within each local population. The warm overwintering temperatures in some areas of the northwest Atlantic may promote early emergence from dormancy, for example in the Gulf of Maine (Durbin et al., 1997), where the exceedingly warm (for this species) overwintering temperatures may force exit from dormancy in late summer and entry into dormancy later in the fall by subsequent cohorts (Maps et al., 2012). Short dormancy duration in these warm areas, and late entry in fall, may contribute to the explanation of the relatively short period in late winter (days 20–60: Fig. 10) over which stage CVs emerge from dormancy throughout the North Atlantic. The alternative (although not necessarily mutually exclusive) hypothesis of photo-awakening (Speirs et al., 2004), in which photoperiodic cues are invoked to explain synchronicity of arousal from dormancy, cannot be ruled out, however.

Future advances in understanding of dormancy timing and duration and the mechanisms to explain it will require continued collection of time series data and quantitative application of the lipid accumulation/metabolism hypothesis across data sets. Many of the data sets compiled here do not have sufficient frequency of sample collection or length of time series to allow accurate determination of dormancy timing and duration. There are fewer long-term offshore time series in the northwest Atlantic than in the northeast Atlantic, and none in the middle of the basin. Further insight into dormancy control will require time series observations at strategically selected stations at relatively high frequency (semi-monthly to monthly) over several years (Ji et al., 2010), including biochemical and perhaps genetic measurement of dormancy state in order to accurately characterise regional and individual differences in timing and duration of dormancy.

Reproductive rates

Egg production rates (EPRs) are clearly strongly related to food availability throughout the North Atlantic, but the goal of precisely predicting EPRs for *C. finmarchicus* from simple environmental variables, such as chlorophyll concentration and temperature, and female size remains elusive, in light of the high degree of variability reported here (e.g. Figs. 15 and 16). This variability is not surprising, since many other factors can also influence individual EPRs. For example, EPRs are affected by food type (Marshall and Orr, 1972; Niehoff et al., 1999; Jónasdóttir et al., 2002; Niehoff, 2004) and although diatoms are generally dominant during spring, in some regions blooms of other phytoplankton taxa, which may be inferior foods, such as the colonial prymnesiophyte *Phaeocystis* spp., are common (Soreide et al., 2008). Young females that have recently molted may take several days to attain reproductive maturity and until then are not reproductively active, effectively lowering estimated per capita EPR (Plourde and Runge, 1993; Niehoff et al., 1999, 2002). As well, during the later stages of the spring bloom old females may be less fecund (Diel and Tande, 1992; Hirche et al., 1997; Head et al., 2013a,b) and may start to accumulate fat (Head et al., 2013a). At stations where chlorophyll concentrations are very low, particularly in post-bloom conditions, females are known to feed omnivorously (Ohman and Runge, 1994; Runge and de Lafontaine, 1996; Ohman and Hirche, 2001; Levinsen et al., 2000), in which case chlorophyll concentration may not be an appropriate measure of “food” concentration. Moreover, the extent to which contemporaneous estimates of chlorophyll represent female feeding history will also be a factor; in some instances (e.g. patchy, advective environments such as the

RIM station), chlorophyll concentrations may change substantially from day to day.

Temperature undoubtedly influences EPR in laboratory studies (Hirche et al., 1997; Rey et al., 1999), but the effects of changes in temperature *in situ* are not broadly predictable. For example, after the effect of food had been accounted for, temperature had a positive correlation with EPRs in 3 study regions (RIM, LS, ICE(N)), a negative correlation in one (IRM) and no relationship in the other 8 (Table 6). On the other hand, EPR_{max} for females from the WGBB region during spring, where temperatures are close to 0 °C, were four times lower than for those from the SS, where average temperatures are only ~2 °C higher (cf. Figs. 4 and 15). Also, EPRs in the WGBB in spring were substantially lower than those measured for females that were collected at *in situ* temperatures of ~9 °C and switched to 0 °C (Hirche et al., 1997; Kjellerup et al., 2012) and females collected from the WGBB during the spring bloom took several days to increase their EPRs when fed and incubated at higher temperatures in the laboratory, implying that temperature effects may be relatively persistent. The inability of *C. finmarchicus* females to produce eggs at high rates at these low temperatures may be one factor limiting the species northern distribution at this time, since the periods of the year over which high food concentrations co-occur with acceptably high temperatures decrease in duration with increasing latitude, so that the effective reproductive and growth seasons are shorter. Indeed, it may be that *C. finmarchicus* populations are not currently self-sustaining in the WGBB. This region is, however, downstream of an important production area in the eastern Labrador Sea, which may serve as a source of overwintering females on an annual basis.

Temperature during the spring period was negatively or positively related to female size in 7 study regions, and female size was positively related to egg production residuals in 3 regions (GB, RIM, LS). In some regions the changes in temperature were probably associated with differences in water masses among stations, and thus in the source populations for females (e.g. IRM, NNWS) of varying sizes. In others, however, increasing temperatures may reflect the warming of the surface layers over the spring period, and the entry of larger females, possibly from the G1 generation, into the egg-laying population (e.g. GB). In addition, in stratified waters in particular, the selection of which temperature accurately represents the temperature of vertically mobile females is in itself problematic.

Given the observed variability in the relationship between egg production rate and chlorophyll a standing stock across regions, it is not possible at this time to identify any general parameterization of egg production response to measures of food availability and temperature across the North Atlantic. In some regions there is a useful fit (e.g. $r^2 > 0.2$) to an Ivlev-type relationship in spring (GB and RIM; arguably also SS, LS and ICE(N)); in others (IRM, ICE (S), BIS, NNWS), there appears to be no relationship with chlorophyll standing stock. It may be that each region has its own particular relationship (or lack thereof), reflecting regional differences in dynamics and species composition of primary producers, as well as possible physiological differences in resident *C. finmarchicus*. There is evidence (Figs. 15 and 16; Table 5) for broad regional differences in maximum egg production rate (35–60 eggs female⁻¹ d⁻¹ in the northwest Atlantic compared to 20–30 eggs female⁻¹ d⁻¹ in the northeast Atlantic) and in critical concentrations, which range from 53–94 mg chl a m⁻² in the upper 30 m (1.8 and 3.1 mg m⁻³) in the northwest Atlantic, compared to 17–57 mg chl a m⁻² (0.6–1.9 mg m⁻³) in the northeast Atlantic (with the exception of a very different relationship at ICE(N)). This factor of two difference may reflect the generally smaller female size in the northeast Atlantic, although the average prosome length of experimental females from GB was about the same as the one for experimental females from the Norwegian Sea, where maximum

egg production rates were lower by nearly a factor of three. Alternatively, these broad regional differences in egg production characteristics may reflect physiological and perhaps genetically differentiated responses to the food, light and temperature regimes on the two sides of the North Atlantic. Consistent with this hypothesis is the apparent divergence in conclusions with respect to the use of internal lipid stores to produce eggs prior to the spring bloom; evidence for this process has been found in the northeast Atlantic (e.g. Niehoff et al., 1999; Richardson et al., 1999) but not in the northwest Atlantic (e.g. Plourde and Runge, 1993; Durbin et al., 2003). Production of eggs prior to the spring bloom may reflect the fact that females in the northeast Atlantic are adapted to the lower food conditions (as represented by chlorophyll standing stock) that are generally found there. Differences in number of eggs could to some extent be compensated by egg size, which we have not measured and would reflect genetic difference between the western and eastern *C. finmarchicus* populations. To our knowledge egg size has not been compared among sites on a basin scale.

Analysis of prosome length-dry mass measurements for female *C. finmarchicus* also suggests differences between northwest and northeast Atlantic populations. Prosome length-dry mass relationships were determined for females on Georges Bank (Runge et al., 2006) and in the sea around Iceland (Gislason, 2005). Based on these relationships, a 2.6 mm female should have a dry mass of 289 µg on Georges Bank and 165 µg off Iceland, a difference of about 40%. The C and N contents of a 2.6 mm female on Georges Bank are predicted to be 135 µg and 29 µg, respectively and a similar relationship was found for females collected in the Labrador Sea (Head et al., 2013a). At Stn OWS Mike (SNWS), Irigoien et al. (1998) reported a carbon content of 50 µg and nitrogen content of 12 µg for females with an average PL of 2.6 mm (Niehoff et al., 1999) collected between April and June. From these measurements, and using the spring EPR_{max} for the SNWS from Table 5 and literature egg C and N contents (Runge and Plourde, 1996), C and N specific EPR_{max} values of 11.8% body C d⁻¹ and 9.4% body N d⁻¹ can be estimated, somewhat higher than those reported for Georges Bank or the Labrador Sea (8.5% and 7.2% for C and N specific rates, respectively). Similar calculations were made for the SS and WGBB regions, using EPR_{max} values from Table 5 and female C and N contents of 168 and 33 µg for the SS (R. Campbell, unpubl. data) and 109 and 21 µg for the WGBB (Kjellerup et al., 2012). For these regions the C and N specific EPR_{max} values were 5.1% body C d⁻¹ and 4.9% body N d⁻¹ (SS) and 2.5% body C d⁻¹ and 2.3% body N d⁻¹ (WGBB). *In situ* temperatures were 5–9 °C for GB, 3–8 °C for the LS, between –1 to +6 °C on the SS, and between –1.58 and +2 °C in the WGBB region. Thus, over four regions in the NW Atlantic, C and N specific EPR_{max} values appear to increase with increasing temperature. In the NE Atlantic (SNWS), average spring temperature was similar (~7 °C) to those on GB and in the LS, but C and N specific EPR_{max} values were higher. Head et al. (2013a) estimated a maximum C specific EPR of 5.8% body C d⁻¹ and a maximum N specific rate of 5.9% d⁻¹ for females from a northern Norwegian fjord, using maximum observed EPRs (Diel and Tande, 1992) and average female C and N contents (Tande, 1982). Here, the average temperature was ~5 °C, so that both the maximum EPR and temperature were lower than in the SNWS. From these few datasets the extent to which C and N specific EPR_{max} values are the same at similar temperatures among regions, or have similar relationships with temperature, is unclear. More observations of EPRs in concert with measurements of female body C and N are needed to explore this and the question of physiological differences among regions and populations remains open.

Mortality

We have extended the VLT approach applied by Plourde et al. (2009b) to a broader dataset based on several national monitoring

programs in the northeast and northwest Atlantic. Results for the population active growth period show a hyperbolic decrease in mortality rate from the early to late life stages, with values that are generally consistent in magnitude with those determined by Ohman et al. (2002). In most cases regional variations were relatively small, which is surprising given the likelihood of different predator fields among regions. Mortality rates of older copepodite stages (CIV–V) active in the surface layer are highest on the shelves and positively correlated with temperature, suggesting there may be higher predation mortality by visually guided predators in shelf ecosystems than in the deep ocean. When integrated with stage-specific development times to construct development trajectories and to estimate daily recruitment, there were relatively small differences (no more than a factor of two, Fig. 18) in copepodite stage-specific daily mortalities and very similar survival trajectories from CI to CV across the different regions (Figs. 18 and 20). In contrast to the copepodite stages, differences in daily mortality rates in egg–CI, probably mostly caused by mortality in the egg and early naupliar stages (i.e., Ohman et al., 2004; Plourde et al., 2009a), appear to translate into markedly different survival trajectories, particularly in cold habitats (<6 °C). Here, small differences in daily mortality rates of egg–CI resulted in 5–6 times lower survival rates in regions where they were likely to be co-occurring with large the Arctic congeners *C. hyperboreus* and *C. glacialis* (Fig. 20). Our analysis identifies these species as potentially significant sources of mortality for the early stages of *C. finmarchicus* in cold regions that are influenced by Arctic water, e.g. the Labrador and Newfoundland shelves. Indeed, predation by these arctic species may represent a significant constraint on expansion of the species' range northward in response to warming surface waters. As evidenced by the observations of seasonal demography, predation by these Arctic copepodites on *C. finmarchicus* eggs and nauplii appears to have the effect of displacing the recruitment window for the latter to a period either late in or after the bloom, resulting in a mismatch with optimal food conditions and thus lower productivity relative to warmer regions (Figs. 8 and 9). A similar 'intraguild predation' interaction has been hypothesised to control copepod species succession at Station India, a *C. finmarchicus* dominated system where the abundance of several small copepod species was inversely proportional to *C. finmarchicus* abundance, which, it has been suggested, leads to their optimal recruitment window being displaced outside the period when *C. finmarchicus* were active in the surface layer (Irigoin and Harris, 2006).

We did not investigate mortality and survival of *C. finmarchicus* during the overwintering period on a basin-wide scale because existing data sets were inadequate for such a study. Elsewhere, however, estimates of mortality rates for dormant *C. finmarchicus* are generally very low ranging from 0.004 to 0.027 d⁻¹, so that overwintering mortality does not appear to be very important compared to mortality at other times of the year. On the other hand, predation on overwintering *Calanus* may be important in certain locations. For example Norwegian fjords, with mesopelagic fish present had mortality rates up to three times higher (0.011–0.027 d⁻¹) than one that had only invertebrate predators (0.008–0.009 d⁻¹; Bagoeien et al., 2001). Few estimates of overwintering mortality have been made for deep oceanic regions although there is one that has suggested that mortality of overwintering *C. finmarchicus* is substantially lower in Irminger Sea and Iceland Basin (0.004 d⁻¹) relative to shelf locations, a difference mainly attributed to a reduced vertical overlap between the overwintering stock and mesopelagic fishes such as myctophids in the deeper regions (Bagoeien et al., 2001; McLaren et al., 2001; Gislason et al., 2007; Pepin, 2013). This limited degree of vertical overlap in the centres of distribution of *C. finmarchicus*, could represent the expression of long-term evolutionary processes resulting in an optimal life-cycle strategy that minimizes mortality for the species as a whole (Gislason et al., 2007).

Modeling mesozooplankton distribution and abundance in the North Atlantic in the context of climate change: statistical and spatial dynamics modeling approaches

The compilation of information reported here represents a step toward modeling the population distribution and dynamics of *C. finmarchicus*, and in turn, their responses to climate change drivers over the North Atlantic. In the recent years, two main modeling approaches, statistical (niche-based) and dynamic (mechanistic or process-based), have been employed to improve our understanding of distribution patterns in *Calanus* spp. in the northern North Atlantic.

Statistical-based modeling is based upon the ecological niche theory relating species occurrence (or abundance) to environmental variables and food as predictors. This approach has been termed habitat suitability (Hirzel et al., 2002), species distribution (Elith and Leathwick, 2009) or habitat distribution (Guisan and Zimmermann, 2000) modelling. Although initially habitat models were applied to terrestrial species (especially vascular plants, Elith and Leathwick, 2009), more recently they have also been applied to a wide variety of marine species including zooplankton to provide projections of future climate-driven shifts in species distributions (Beaugrand et al., 2002, 2008; Helaouët and Beaugrand, 2007, 2009; Reygondeau and Beaugrand, 2011; Helaouët et al., 2011). Most of the zooplankton studies use distance measures, in contrast to the more capable generalised additive (Chust et al., 2013b) and Maximum Entropy models (Provan et al., 2009). Model validation and variable selection are critical steps in order to extrapolate habitat models to conditions outside of those used to generate the model, for instance for future climate scenarios or other areas (e.g. Valle et al., 2011). This is especially problematic for modeling consequences of future climate change. Most of the habitat modeling software (BIOTRIM (Nix, 1986), Maxent (Elith et al., 2011), *dismo* R package (Hijmans and Elith, 2013), Ecological Niche Factor Analysis (ENFA, Hirzel et al., 2002), BIOMOD (Thuiller et al., 2009), openModeller (Muñoz et al., 2009)) were conceived to be applied for species with low spatial variation throughout the seasonal cycle, such as sessile organisms, from a set of spatial layers of environmental variables. Species with high seasonality such as zooplankton need to be modeled taking into account the temporal domain explicitly (Chust et al., 2013b).

The coupled physical-life history modeling approach is mechanistic and mainly based upon factors affecting spatial population dynamics (reproduction, mortality and migration rate). There are two distinct methods for simulating the spatial dynamics of plankton, namely the Lagrangian (Individual Based Models IBMs) and Eulerian approaches (reviewed in Runge et al., 2005). Several models have been developed to simulate the spatial and population dynamics of *C. finmarchicus* both using IBMs (e.g. Carlotti and Nival, 1992; Carlotti and Wolf, 1998; Miller et al., 1998; Hjøllø et al., 2012; Ji et al., 2012; Maps et al., 2012; Huse et al. (submitted for publication); Pepin et al., 2013), and Eulerian (e.g.: Bryant et al., 1997; Lynch et al., 1998; Tittensor et al., 2003; Zakardjian et al., 2003; Speirs et al., 2004, 2006; Slagstad and Tande, 2007; Maps et al., 2012) models. Eulerian models are numerically more efficient than IBMs. On the other hand, the mechanistic process formulation of IBMs permits a more detailed biological description of individuals (Grimm and Railsback, 2005; Maps et al., 2012). A 3-D IBM for *C. finmarchicus* in the Norwegian Sea has been developed that takes into account growth, mortality, movement and reproduction of *C. finmarchicus* as well as adaptive traits, which control its interaction with the environment (Hjøllø et al., 2012). This model addresses the entire life cycle of *C. finmarchicus*; the main life history features and vertical movement are emergent properties resulting from many evolved generations using a genetic algorithm. A genetic algorithm procedure (Record

et al., 2010) has also been used in a *Calanus* IBM model to determine values for “soft parameters”, for which available knowledge only allows a range of values to be specified (Maps et al., 2012). Uses of coupled physical–biological models in the context of understanding *C. finmarchicus* distribution and abundance include identification of advective and life history factors determining biogeographical boundaries (Ji et al., 2012), assessment of advection vs. local production in maintaining regional abundance (Zakardjian et al., 2003; Speirs et al., 2006), investigation of sources of supply (Pepin et al., 2013) and role of life history in scenarios of climate forcing (Maps et al., 2012). Variations of these models will undoubtedly see application in future assessments of *C. finmarchicus* population abundance in relation to ecosystem based management of fishery resources.

Compared with habitat suitability models, spatial dynamical models require extensive computational resources, and can only be applied when demographical, physiological, and life traits of species are well known. On the other hand, habitat modeling studies have often neglected dispersal limitation and advection, even though they can play an important role in driving plankton spatial distributions (Irigoien et al., 2011; Chust et al., 2013a,b). In line with taking a balanced view between the importance of the role of dispersal limitation and of niche partitioning on zooplankton spatial distributions (Irigoien et al., 2011, and Chust et al., 2013b), research efforts should focus on integrating the two mechanisms in the modelling approach for zooplankton species, in the same way as has already been done for fish and invertebrates (e.g. Cheung et al., 2009). Thus, a detailed dynamic approach to understanding species distribution in relation to habitat can only be undertaken for species like *C. finmarchicus* that are clearly of fundamental functional importance for the ecosystem, such that resources can be devoted to acquiring the necessary data. As a direction of future research, a synthesis of the two approaches, focusing on *C. finmarchicus*, might provide insight into the likely effects of climate forcing on abundance and distribution of species in the North Atlantic. In order to obtain a synoptic view of the zooplankton species community, coupling of simplified life history models to the physical circulation and application of statistical habitat models is suggested.

Summary, research needs and directions

The great advancement in habitat suitability and life history and coupled physical–biological modeling of *C. finmarchicus* populations over the past 10 years puts new demands for abundance and environmental data and accurate and comprehensive parameterization of life history processes. Our analysis of the combined distributional, demographic and physiological datasets has shown that the best approach to model the distribution of *C. finmarchicus* requires a combination of different approaches to monitoring data. While CPR data show the basin scale surface distribution of the species, CPR coverage does not include the population centres in the Norwegian Sea or the Labrador Sea; net sampling provides more targeted information on these important areas as well as on the vertical distributions of *C. finmarchicus* populations. Vertical distribution data can be crucial in identifying ambient temperatures for modelling purposes and for defining critical temperature ranges within which the species may thrive or fail to survive. A more thorough analysis using net and CPR data is recommended to explore this issue. We observed the highest population densities were within the deep basins of the Labrador and Norwegian Seas and that locations not closely connected to these deep basins by advection, had lower population densities (such as many North Sea sites). High winter mortality in shallow water regions may be why these sites need replenishment from the deep basins.

Phenology associated with the *C. finmarchicus* life cycle was variable across the North Atlantic. There was a 3.5 month difference in timing of the occurrence of the first generation, with the western sites showing later occurrences relative to the spring phytoplankton bloom than the eastern sites. We found that temperatures at which peak abundance occurred varied between 3 and 15 °C, with highest population densities at about 13 °C. It is currently unclear whether the process models are able to reflect these differences in timing and if they do not, we need to improve model parameterization.

Our analyses also yielded seasonal and spatial differences in stage specific mortality. Mortality rates of young stages were particularly high in cold water areas, leading us to suggest significant predation by the larger congeners, *C. hyperboreus* and *C. glacialis*, which are abundant in these areas in spring. This hypothesis warrants a proper field investigation. In the population centres of *C. finmarchicus* the major predators are other invertebrates (e.g. chaetognaths, euphausiids, etc.), mesopelagic and pelagic fish, and possibly adult females, the latter via cannibalistic feeding on their own eggs and nauplii. We have cited several investigations where predation impact has been quantified and related to the annual production of *C. finmarchicus*. Precise quantification of the impact of predation on *C. finmarchicus* populations cannot be accomplished, however, until the population sizes of the predators and prey are more accurately characterised. Due to short life spans and rapid and spatially variable developmental rates of both prey and some of the predators, this cannot be solved by more observations alone, but must involve the application of population dynamic models, preferably with data assimilation capabilities. Representative sampling of predator stomachs and verification of predation by other methods on a population scale is another largely neglected but challenging task, given the complexity and costs involved. Studies on mortality during the overwintering period are also needed in order to describe and understand the relative role of the physical environmental conditions and different predator guilds (fishes, invertebrates) in controlling the survival success during this portion of the life cycle in regions across the entire *C. finmarchicus* distribution range. Estimating winter mortality in shelf areas is important in order to understand the drivers of population dynamics of *C. finmarchicus* in these habitats and the importance of these overwintering populations to potential predators that reside on the shelves and stay active during the winter.

There remain questions about the generality of parameterization of growth, reproduction and diapause timing across the North Atlantic. Further detailed investigations of egg production rate responses across regions are needed in order to resolve possible methodological sources for differences between results obtained using females from either the northwest or the northeast Atlantic. The hypothesis that apparent cross-basin differences in egg production and female body size are the consequence of genetically differentiated physiological responses to habitat differences in food conditions, temperature and light can be tested against the alternative: namely, that the observations presented here are the consequences of differences in food and body size alone. Cross basin experiments investigating growth, development and reproductive responses of *C. finmarchicus* collected from both northwest and northeast Atlantic sites under identical experimental conditions would provide insight, as would a careful cross-basin comparison of body size dry mass, carbon and nitrogen relationships. Our quantitative understanding of timing of diapause entry and exit is still rudimentary. Improved, long term and high frequency (i.e., semi-monthly to monthly) time series sampling at a few selected sentinel sites for demographic analysis combined with biochemical (i.e., body mass, lipid content, RNA/DNA ratios: Wagner et al., 1998) and perhaps genetic indicators of diapauses/active state would be useful for further testing of dormancy hypotheses.

Acknowledgements

This work was part of the ongoing research within the EU FP7 program (EURO-BASIN; Basin-scale Analysis, Synthesis & INtegration ENV.2010.2.2.1-1; www.euro-basin.eu). The work was supported by the Research Council of Norway through projects HARVEST (178447) and ECCO (200508).

J. Runge and J. Pierson were supported by the U.S. National Science Foundation through awards OCE-0815336 and OCE-1041081.

Appendix A. *Calanus finmarchicus* demographic patterns

Descriptions of the data sets used to characterise demographic patterns across the North Atlantic are summarized in Table 1. Here we provide detailed figures of seasonal patterns of abundance by stage in relation to temperature and chlorophyll concentration at the sampling sites across the North Atlantic analysed in the demographic, dormancy and mortality sections above (Fig. A1–A6). Details on sampling depth of chlorophyll and temperature can be read from the axes labels.

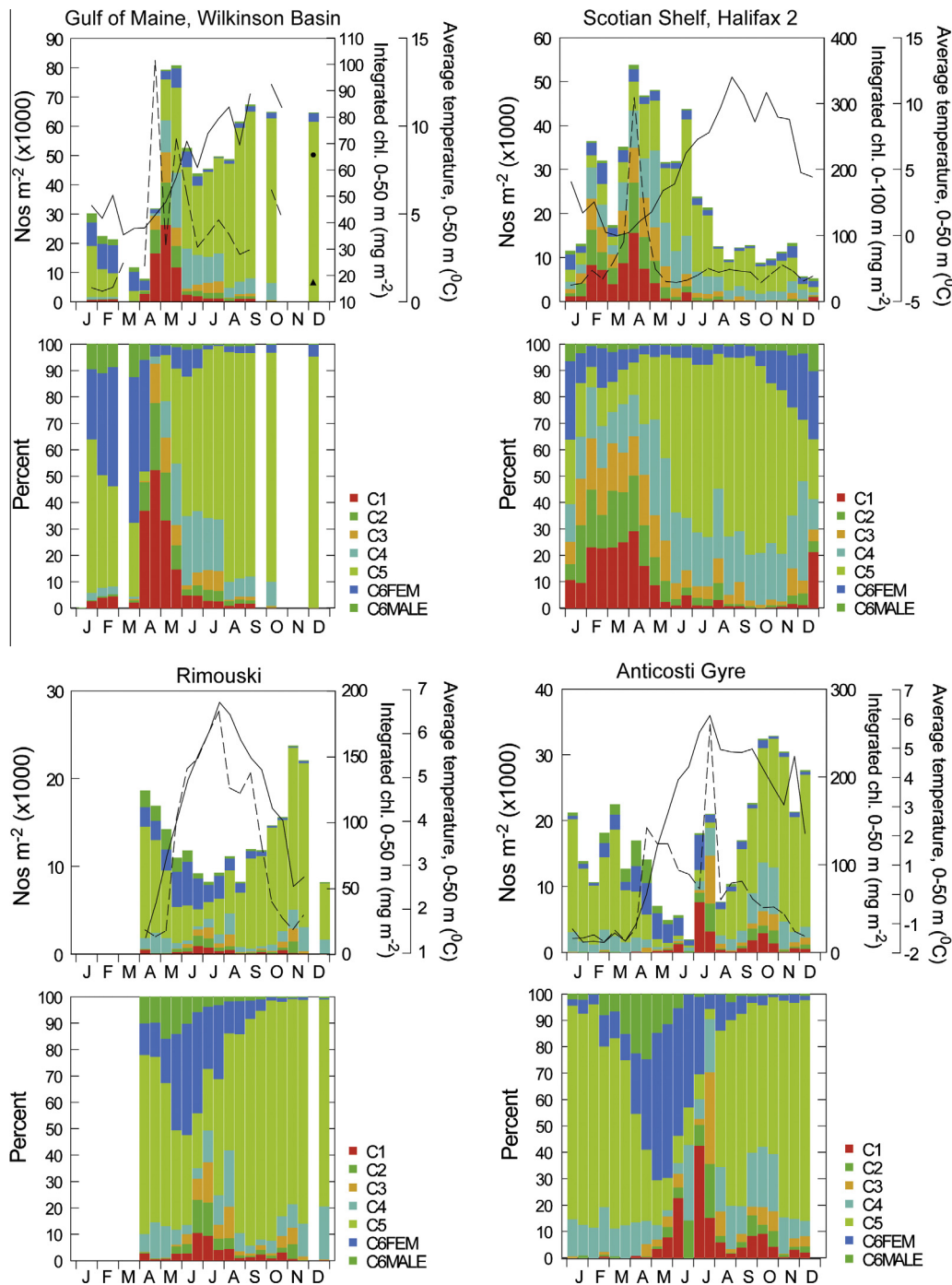


Fig. A1. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).

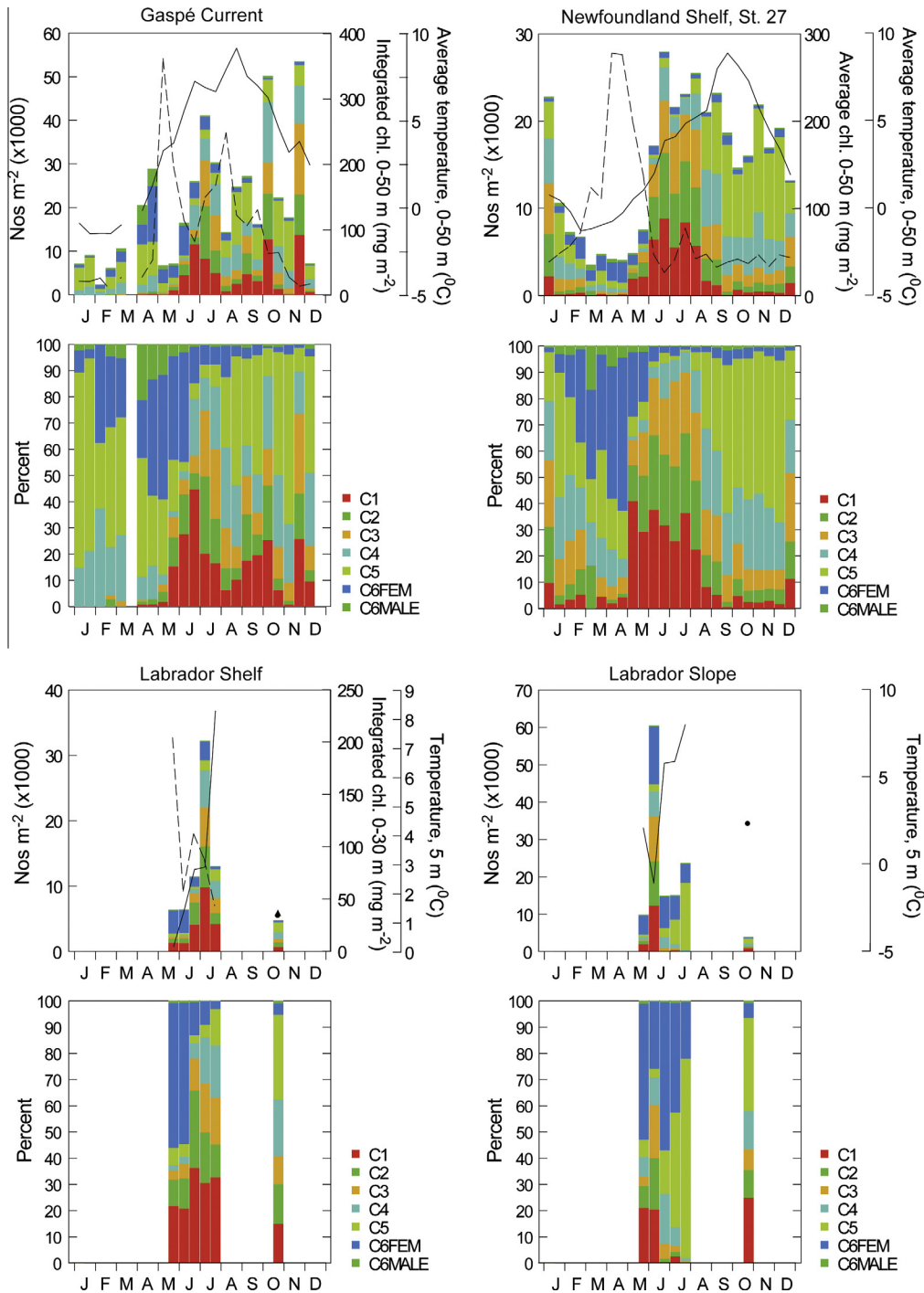


Fig. A2. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).

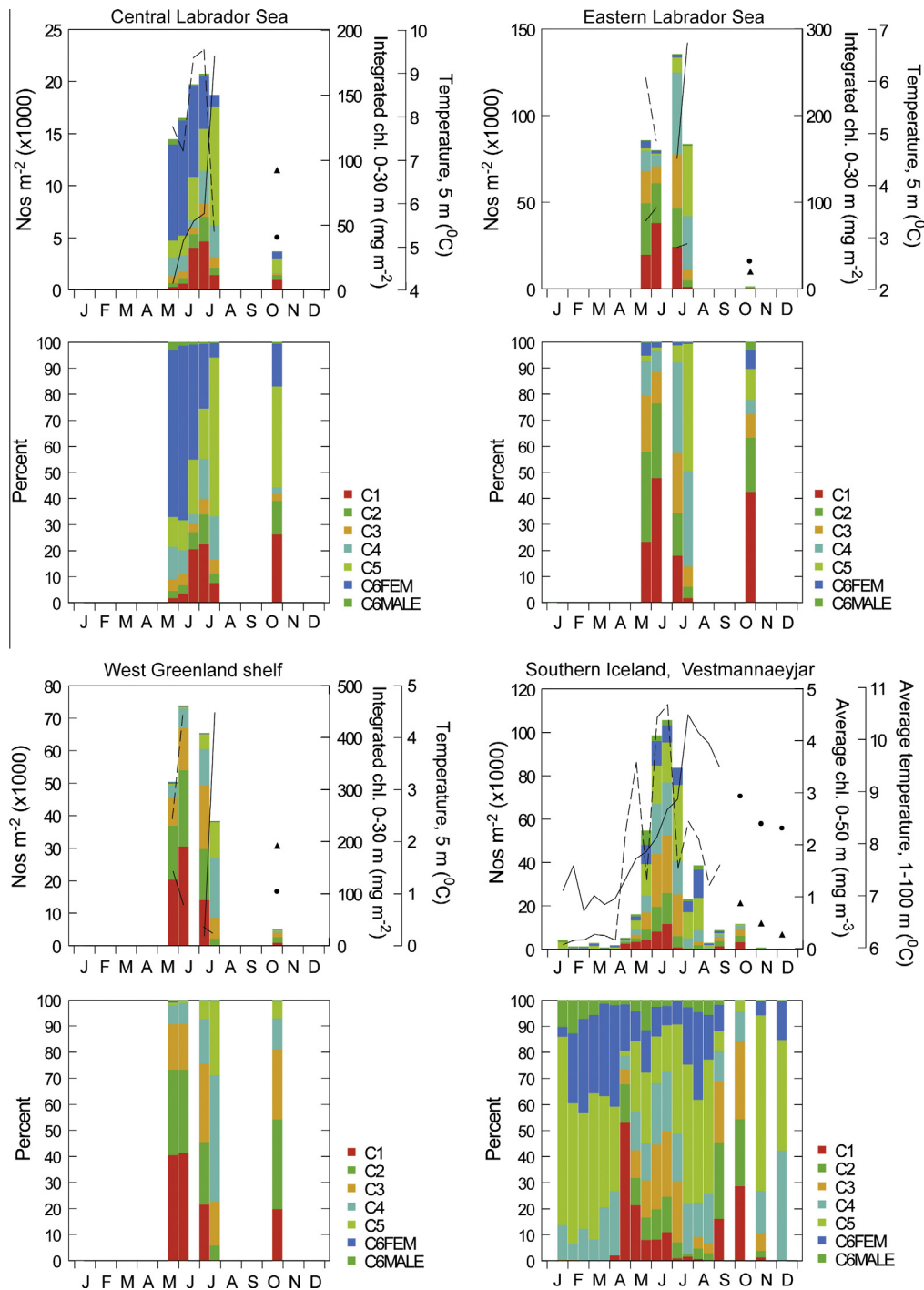


Fig. A3. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).

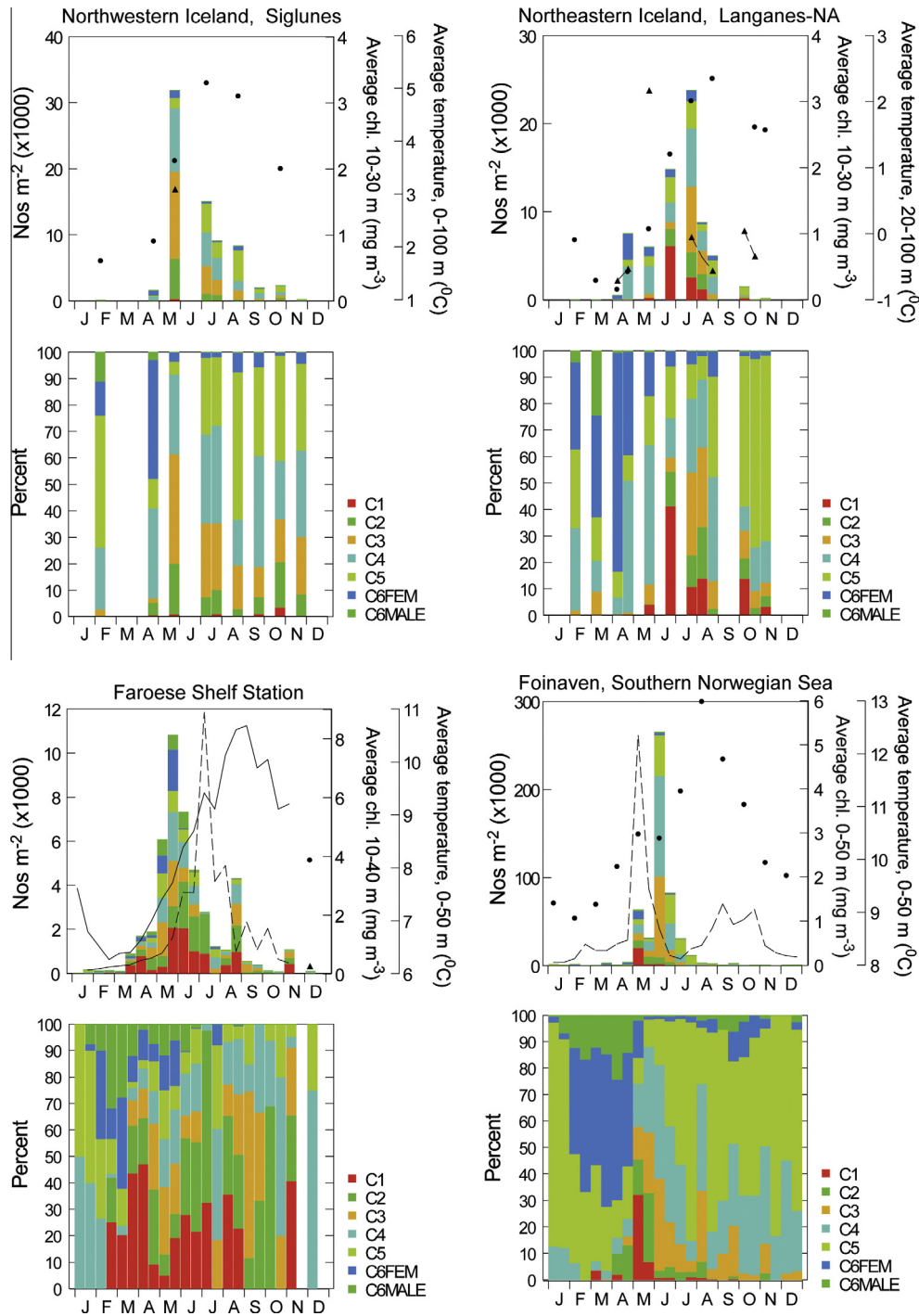


Fig. A4. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).

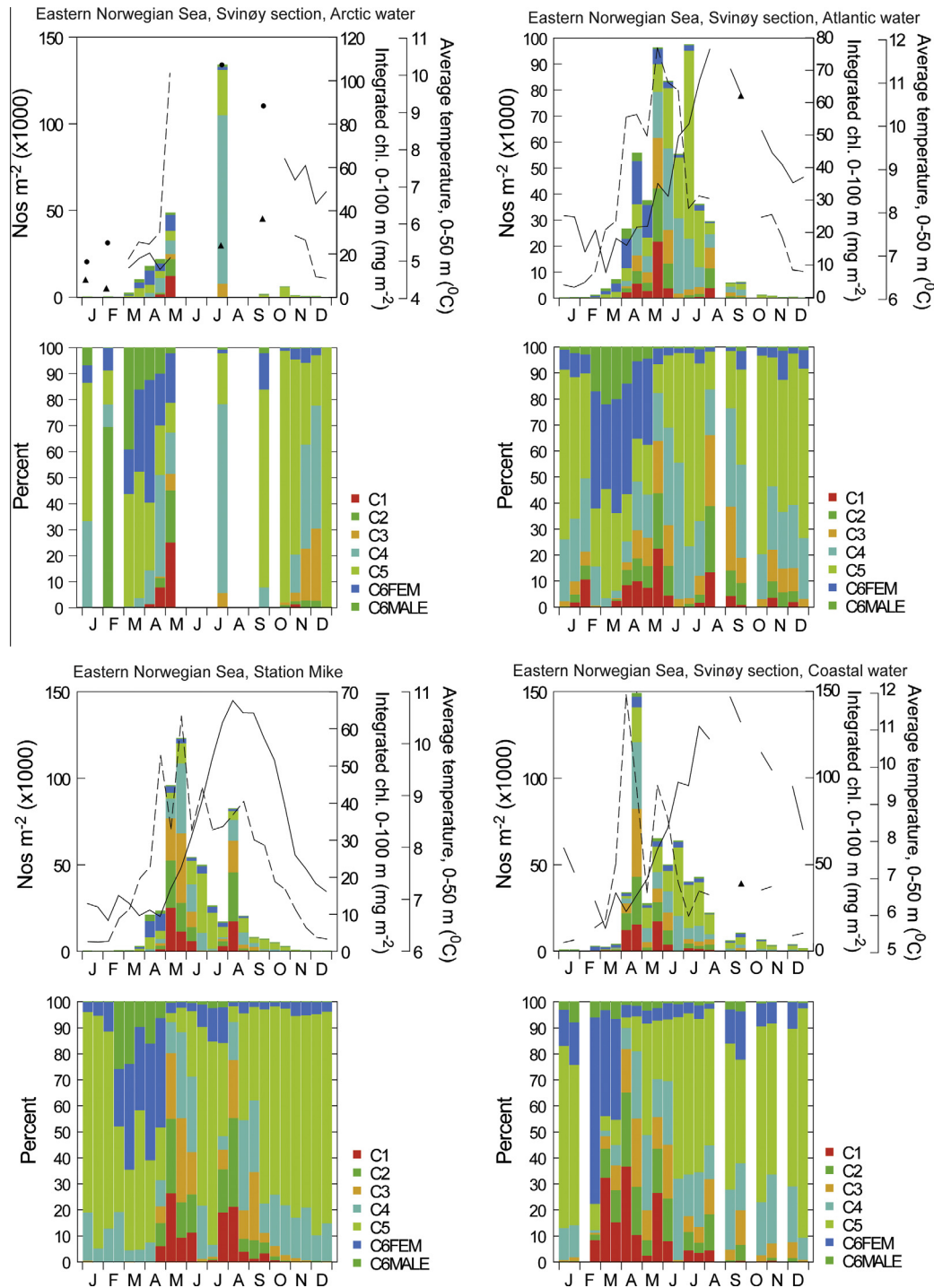


Fig. A5. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms), Temperature (solid line) and chlorophyllII (dashed line).

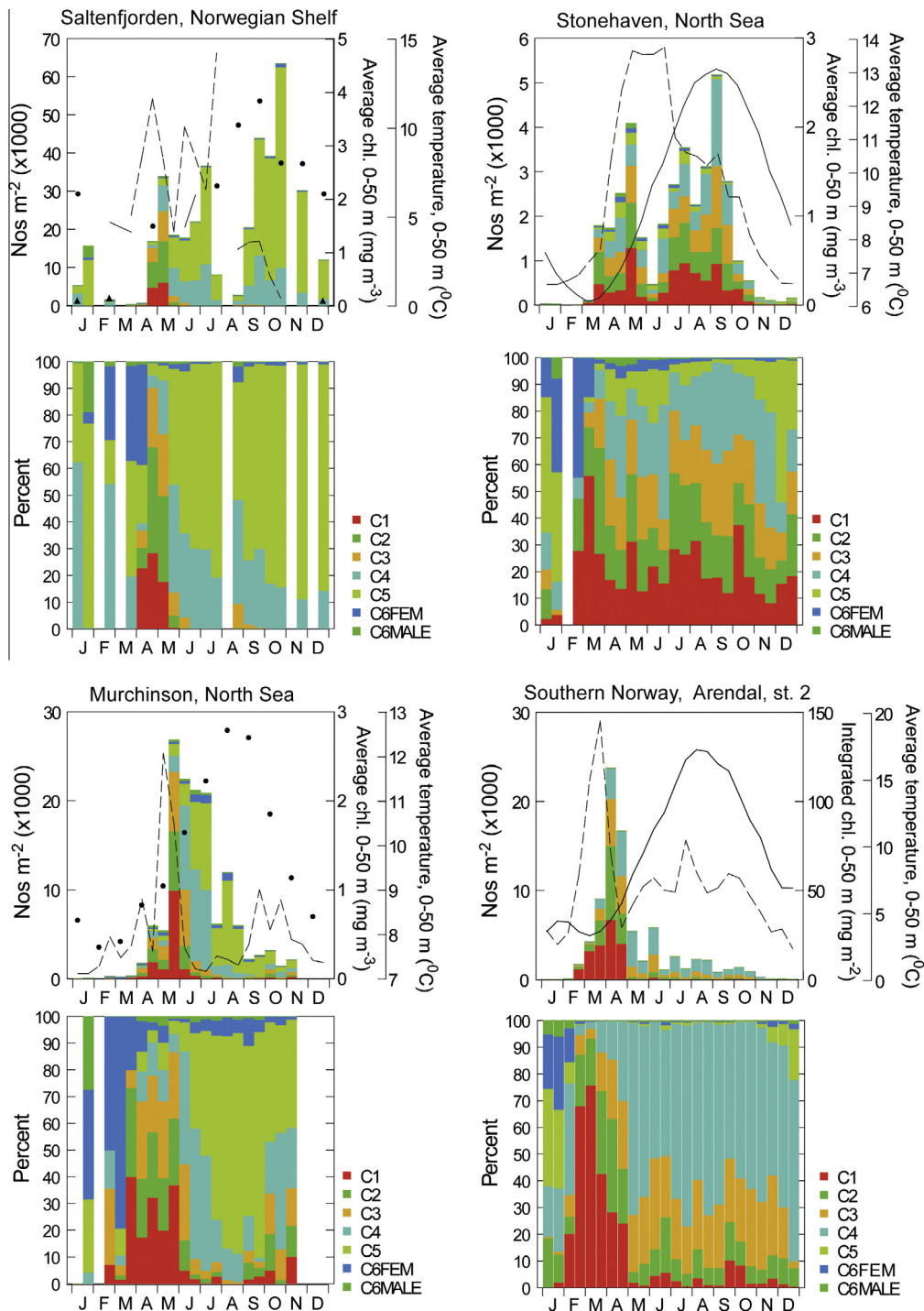


Fig. A6. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).

References

- Aksnes, D.L., Blindheim, J., 1996. Circulation patterns in the North Atlantic and possible impact on population dynamics of *Calanus finmarchicus*. *Ophelia* 44, 7–28.
- Anderson, J.T., 1990. Seasonal development of invertebrate zooplankton on Flemish Cap. *Marine Ecology Progress Series* 67, 127–140.
- Astthorsson, O.S., Gislason, A., 2003. Seasonal variations in abundance, development, and vertical distribution of *Calanus finmarchicus*, *C. hyperboreus* and *C. glacialis* in the East Icelandic Current. *Journal of Plankton Research* 25, 843–854.
- Bagoien, E., Kaartvedt, S., Aksnes, D.L., Eiane, K., 2001. Vertical distribution and mortality of overwintering *Calanus*. *Limnology and Oceanography* 46, 1494–1510.
- Bagoien, E., Melle, W., Kaartvedt, S., 2012. Seasonal development of mixed layer depths, nutrients, chlorophyll and *Calanus finmarchicus* in the Norwegian Sea – a basin-scale habitat comparison. *Progress in Oceanography* 103, 58–79.
- Basedow, L., Tande, K.S., 2006. Cannibalism by female *Calanus finmarchicus* on naupliar stages. *Marine Ecology Progress Series* 327, 247–255.
- Batten, S.D., Clark, R., Flinkman, J., Hays, G., John, E., John, A.W.G., Jonas, T., Lindley, J.A., Stevens, D.P., Walne, A., 2003a. CPR sampling: the technical background, materials and methods, consistency and comparability. *Progress in Oceanography* 58, 193–295.
- Batten, S.D., Walne, A.W., Edwards, M., Groom, S.B., 2003b. Phytoplankton biomass from continuous plankton recorder data: an assessment of the phytoplankton colour index. *Journal of Plankton Research* 25, 697–702.
- Behrenfeld, M.J., 2010. Abandoning Sverdrup's Critical Depth Hypothesis on phytoplankton blooms. *Ecology* 91, 977–989.
- Beaugrand, G., Edwards, M., Brander, K., Luczak, C., Ibanez, F., 2008. Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. *Ecology Letters* 11, 1157–1168.
- Beaugrand, G., Reid, P.C., Ibáñez, F., Lindley, J.A., Edwards, M., 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* 296, 1692–1694.
- Bonnet, D., Titelman, J., Harris, R., 2004. *Calanus* the cannibal. *Journal of Plankton Research* 26, 937–948.
- Bonnet, D., Richardson, A., Harris, R., Hirst, A., Beaugrand, G., Edwards, M., Ceballos, S., Diekmann, R., Lopez-Urrutia, A., Valdes, L., Carlotti, F., Molinero, J.C., Weikert, H., Greve, W., Lucic, D., Albaina, A., Yahia, N.D., Umani, S.F., Miranda, A., dos Santos, A., Cook, K., Robinson, S., de Puelles, M.L.F., 2005. An overview of *Calanus helgolandicus* ecology in European waters. *Progress in Oceanography* 65, 1–53.
- Broms, C., Melle, W., 2007. Seasonal development of *Calanus finmarchicus* in relation to phytoplankton bloom dynamics in the Norwegian Sea. *Deep-Sea Research Part II* 54, 2760–2775.
- Broms, C., Melle, W., Kaartvedt, S., 2009. Oceanic distribution and lifecycle of *Calanus* species in the Norwegian Sea and adjacent waters. *Deep-Sea Research Part II* 56, 1910–1921.
- Bryant, A.D., Heath, M., Gurney, W.S.C., Beare, D.J., Roberston, W., 1997. The seasonal dynamics of *Calanus finmarchicus*: development of a three-dimensional structured population model and application to the North Sea. *Journal of Sea Research* 38, 361–379.
- Bugden, G.L., 1991. Changes in the temperature-salinity characteristics of the deeper waters of the Gulf of St. Lawrence over the past several decades. In: Theriault, J.-C. (Ed.), *The Gulf of St. Lawrence: small ocean or big estuary?* Canadian Special Publication of Fisheries and Aquatic Sciences 113, 139–147.
- Cabal, J., Harris, L.R., Head, E.J.H., 1997. Egg production rates of *Calanus finmarchicus* in the Northwest Atlantic (Labrador Sea). *Canadian Journal of Fisheries and Aquatic Sciences* 54, 1270–1279.
- Campbell, R.W., Head, E.J.H., 2000. Egg production rates of *Calanus finmarchicus* in the western North Atlantic: effect of gonad maturity, female size, chlorophyll concentration, and temperature. *Canadian Journal of Fisheries and Aquatic Sciences* 57, 518–529.
- Campbell, R.G., Wagner, M.M., Teegarden, G.J., Boudreau, C.A., Durbin, E.G., 2001. Growth and development rates of the copepod *Calanus finmarchicus* reared in the laboratory. *Marine Ecology Progress Series* 221, 161–183.
- Carlotti, F., Nival, P., 1992. Model of copepod growth and development: moulting and mortality in relation to physiological processes during an individual moult cycle. *Marine Ecology Progress Series* 84, 219–233.
- Carlotti, F., Wolf, K.U., 1998. A Lagrangian ensemble model of *Calanus finmarchicus* coupled with a 1-D ecosystem model. *Fisheries Oceanography* 7, 191–204.
- Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Pauly, D., 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries* 10, 235–251.
- Chust, G., Irigoien, X., Chave, J., Harris, R., 2013a. Latitudinal phytoplankton distribution and the neutral theory of biodiversity. *Global Ecology and Biogeography* 22, 531–543.
- Chust, G., Castellani, C., Licandro, P., Ibaibarriaga, L., Sagarminaga, Y., Irigoien, X., 2013b. Are *Calanus* spp. shifting poleward in the North Atlantic? A habitat modelling approach. *ICES Journal of Marine Science (Advance Access published September 16, 2013)*. <http://dx.doi.org/10.1093/icesjms/fst1147>.
- Clark, K.A.J., Brierley, A.S., Pond, D.W., 2012. Composition of wax esters is linked to diapause behavior of *Calanus finmarchicus* in a sea loch environment. *Limnology and Oceanography* 57, 65–75.
- Conover, R.J., 1988. Comparative life histories of the genera *Calanus* and *Neocalanus* in high latitudes of the northern hemisphere. *Hydrobiologia* 167 (168), 27–142.
- Conway, D.V.P., 2006. Identification of the copepodite developmental stages of twenty-six North Atlantic copepods. *Occasional Publications Marine Biological Association of the UK* 21, 28.
- Corkett, C.J., McLaren, I.A., Sevigny, J.-M., 1986. The rearing of the marine calanoid copepods *Calanus finmarchicus* (Gunnerus), *C. glacialis* Jaschnov and *C. hyperboreus* Kroyer with comment on the equiproportional rule. *Synlogus* 58, 539–546.
- Dalpadado, P., Ellertsen, B., Melle, W., Dommasnes, A., 2000. Food and feeding conditions of Norwegian spring-spawning herring (*Clupea harengus*) through its feeding migrations. *ICES Journal of Marine Science* 57, 843–857.
- Darbyson, E., Swain, D.P., Chabot, D., Castonguay, M., 2003. Diel variation in feeding rate and prey consumption of herring and mackerel in the southern Gulf of St. Lawrence. *Journal of Fish Biology* 63, 1235–1257.
- Debes, H.H., Eliassen, K., 2006. Seasonal abundance, reproduction and development of four key copepod species on the Faroe shelf. *Marine Biology Research* 2, 249–259.
- Debes, H., Eliassen, K., Gaard, E., 2008. Seasonal variability in copepod ingestion and egg production on the Faroe shelf. *Hydrobiologia* 600, 247–265.
- de Young, B., Werner, F.E., Batchelder, H., Carlotti, F., Fiksen, Ø., Hofmann, E., Kim, S., Kishi, M., Yamazaki, H., 2010. Dynamics of marine ecosystems: integration through models of physical-biological interactions. In: Barange, M., Harris, R., Field, J., Hoffman, E., Perry, I., Werner, C. (Eds.), *Global Change and Marine Ecosystems*. Oxford University Press, pp. 89–128.
- Diel, S., Tande, K., 1992. Does the spawning of *Calanus finmarchicus* in high latitudes follow a reproducible pattern? *Marine Biology* 113, 21–31.
- Dommasnes, A., Melle, W., Dalpadado, P., Ellertsen, B., 2004. Herring as a major consumer in the Norwegian Sea. *ICES Journal of Marine Science* 61, 739–751.
- Durbin, E.G., Campbell, R.G., Casas, M.C., Ohman, M.D., Niehoff, B., Runge, J., Wagner, M., 2003. Interannual variation in phytoplankton blooms and zooplankton productivity and abundance in the Gulf of Maine during winter. *Marine Ecology Progress Series* 254, 81–100.
- Durbin, E.G., Runge, J.A., Campbell, R., Garrahan, P., Casas, M., Plourde, S., 1997. Late Fall-Early Winter recruitment of *Calanus finmarchicus* on Georges Bank. *Marine Ecology Progress Series* 151, 103–114.
- Edvardsen, A., Petersen, J.M., Slagstad, D., Semenova, T., Timonin, A., 2006. Distribution of overwintering *Calanus* in the North Norwegian Sea. *Ocean Science* 2, 87–96.
- Elith, J., Leathwick, J.R., 2009. Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics* 40, 677–697.
- Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J., 2011. A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions* 17, 43–57.
- Frajka-William, E., Rhines, P.B., 2010. Physical controls and interannual variability of the Labrador Sea spring phytoplankton bloom in distinct regions. *Deep-Sea Research Part I* 57, 541–552.
- Fratantoni, P.S., MacCartney, M.S., 2010. Freshwater export from the Labrador Current to the North Atlantic Current at the Tail of the Grand Banks of Newfoundland. *Deep-Sea Research Part I* 57, 258–283.
- Fuentes-Yaco, C., Koeller, P.A., Sathyendranath, S., Platt, T., 2007. Shrimp (*Pandalus borealis*) growth and timing of the spring phytoplankton bloom on the Newfoundland-Labrador Shelf. *Fisheries Oceanography* 16, 116–129.
- Gaard, E., Hansen, B., 2000. Variations in the advection of *Calanus finmarchicus* onto the Faroe Shelf. *ICES Journal of Marine Science* 57, 1612–1618.
- Gentleman, W.C., Pepin, P., Doucette, S., 2012. Estimating mortality: clarifying assumptions and sources of uncertainty in vertical methods. *Journal of Marine Systems* 105–108, 1–19.
- Gifford, D.J., Harris, R.P., McKinnell, S.M., Peterson, W.T., St. John, M.A., 2010. Dynamics of marine ecosystems: target species. In: Barange, M., Harris, R., Field, J., Hoffman, E., Perry, I., Werner, C. (Eds.), *Global Change and Marine Ecosystems*. Oxford University Press, pp. 75–88.
- Gilbert, D., Sundby, B., Gobeil, C., Mucci, A., Tremblay, G.-H., 2005. A seventy-two-year record of diminishing deep-water oxygen in the St. Lawrence estuary: the northwest Atlantic connection. *Limnology and Oceanography* 50, 1654–1666.
- Gislason, A., 2005. Seasonal and spatial variability in egg production and biomass of *Calanus finmarchicus* around Iceland. *Marine Ecology Progress Series* 286, 177–291.
- Gislason, A., Astthorsson, O.S., 1998. Seasonal variations in biomass, abundance and composition of zooplankton in the subarctic waters north of Iceland. *Polar Biology* 20, 85–94.
- Gislason, A., Astthorsson, O.S., 2000. Winter distribution, ontogenetic migration, and rates of egg production of *Calanus finmarchicus* southwest of Iceland. *ICES Journal of Marine Science* 57, 1727–1739.
- Gislason, A., Astthorsson, A.S., 2002. The food of Norwegian spring-spawning herring in the western Norwegian Sea in relation to the annual cycle of zooplankton. *SARSIA* 87, 236–247.
- Gislason, A., Astthorsson, O.S., Petursdottir, H., Gudfinnsson, H., Bodvarsdottir, A.R., 2000. Life cycle of *Calanus finmarchicus* south of Iceland in relation to hydrography and chlorophyll a. *ICES Journal of Marine Science* 57, 1619–1627.
- Gislason, A., Eiane, K., Reynisson, P., 2007. Vertical distribution and mortality of *Calanus finmarchicus* during overwintering in oceanic waters southwest of Iceland. *Marine Biology* 150, 1253–1263.
- Gislason, A., Gaard, E., Debes, H., Falkenhaug, T., 2008. Abundance, feeding and reproduction of *Calanus finmarchicus* in the Irminger Sea and on the northern Mid-Atlantic Ridge in June. *Deep-Sea Research Part II* 55, 72–82.
- Gislason, A., Petursdottir, H., Astthorsson, O.S., Gudmundsson, K., Valdimarsson, H., 2009. Inter-annual variability in abundance and community structure of

- zooplankton south and north of Iceland in relation to environmental conditions in spring 1990–2007. *Journal of Plankton Research* 31, 541–551.
- Greene, C.H., Pershing, A.J., 2007. Climate drives sea change. *Science* 315, 1084–1085.
- Grimm, V., Railsback, S., 2005. *Individual-based Modeling and Ecology*. Princeton University Press, Princeton.
- Gudmundsson, K., Heath, M.R., Clarke, E.D., 2009. Average seasonal changes in chlorophyll a in Icelandic waters. *ICES Journal of Marine Science* 66, 2133–2140.
- Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. *Ecological Modelling* 135, 147–186.
- Harms, J.H., Heath, M.R., Bryant, A.D., Backhaus, J.O., Hainbucher, D.A., 2000. Modelling the Northeast Atlantic circulation: implications for the spring invasion of shelf regions by *Calanus finmarchicus*. *ICES Journal of Marine Science* 57, 1694–1707.
- Halvorsen, E., Tande, K.S., Edvardsen, A., Slagstad, D., Pedersen, O.P., 2003. Habitat selection of overwintering *Calanus finmarchicus* in the NE Norwegian Sea and shelf waters off Northern Norway in 2000–02. *Fisheries Oceanography* 12, 339–351.
- Head, E.J.H., Harris, L.R., Petrie, B., 1999. Distribution of *Calanus* spp. on and around the Nova Scotia Shelf in April: evidence for an offshore source of *Calanus finmarchicus* to the central and western regions. *Canadian Journal of Fisheries and Aquatic Sciences* 56, 2463–2476.
- Head, E.J.H., Harris, L.R., Yashayaev, I., 2003. Distributions of *Calanus* spp. and other mesozooplankton in the Labrador Sea in relation to hydrography in spring and summer (1995–2000). *Progress in Oceanography* 59, 1–30.
- Head, E.J.H., Harris, L.R., Ringuette, M., Campbell, R.W., 2013a. Characteristics of egg production of the planktonic copepod, *Calanus finmarchicus*, in the Labrador Sea: 1997–2010. *Journal of Plankton Research* 35, 281–298.
- Head, E.J.H., Melle, W., Pepin, P., Bagoieen, E., Broms, C., 2013b. On the ecology of *Calanus finmarchicus* in the sub-arctic North Atlantic: a comparison of population dynamics and environmental conditions in areas of the Labrador Sea-Labrador/Newfoundland shelf and Norwegian Sea Atlantic and Coast waters. *Progress in Oceanography* 114, 46–63.
- Head, E.J.H., Pepin, P., 2008. Variations in overwintering depth distributions of *Calanus finmarchicus* in the slope waters of the NW Atlantic continental shelf and the Labrador Sea. *Northwest Atlantic Fishery Science* 39, 49–69.
- Head, E.J.H., Pepin, P., 2010. Spatial and inter-decadal variability in plankton abundance and composition in the Northwest Atlantic (1958–2006). *Journal of Plankton Research* 32, 1633–1648.
- Heath, M.R., Astthorsson, O.S., Dunn, J., Ellertsen, B., Gaard, E., Gislason, A., Gurney, W.S.C., Hind, A.T., Irigoien, X., Melle, W., Niehoff, B., Olsen, K., Skreslet, S., Tande, K.S., 2000a. Comparative analysis of *Calanus finmarchicus* demography at locations around the Northeast Atlantic. *ICES Journal of Marine Science* 57, 1562–1580.
- Heath, M.R., Backhaus, J.O., Richardsson, K., McKenzie, E., Slagstad, D., Beare, D., Dunn, J., Fraser, J.G., Gallego, A., Heinbucher, D., Hay, S., Jonasdottir, S., Madden, H., Mardaljevic, J., Schacht, A., 1999. Climate fluctuations and the spring invasion of the North Sea by *Calanus finmarchicus*. *Fisheries Oceanography* 8 (Suppl. 1), 163–176.
- Heath, M.R., Boyle, P.R., Gislason, A., Gurney, W.S.C., Hay, S.J., Head, E.J.H., Holmes, S., Ingvarsdottir, A., Jonasdottir, S.H., Lindeque, P., 2004. Comparative ecology of over-wintering *Calanus finmarchicus* in the northern North Atlantic, and implications for life-cycle patterns. *ICES Journal of Marine Science* 61, 698–708.
- Heath, M.R., Fraser, J.G., Gislason, A., Hay, S.J., Jonasdottir, S.H., Richardson, K., 2000b. Winter distribution of *Calanus finmarchicus* in the Northeast Atlantic. *ICES Journal of Marine Science* 57, 1628–1635.
- Heath, M.R., Lough, R.G., 2007. A synthesis of large-scale patterns in the planktonic prey of larval and juvenile cod (*Gadus morhua*). *Fisheries Oceanography* 16, 169–185.
- Heath, M.R., Rasmussen, J., Ahmed, Y., Allen, J., Anderson, C.I.H., Brierley, A.S., Brown, L., Bunker, A., Cook, K., Davidson, R., Fielding, S., Gurney, W.S.C., Harris, R., Hay, S., Henson, S., Hirst, A.G., Holliday, N.P., Ingvarsdottir, A., Irigoien, X., Lindeque, P., Mayor, D.J., Montagnes, D., Moffat, C., Pollard, R., Richards, S., Saunders, R.A., Sidey, J., Smerdon, G., Speirs, D., Walsham, P., Waniek, J., Webster, L., Wilson, D., 2008. Spatial demography of *Calanus finmarchicus* in the Irminger Sea. *Progress in Oceanography* 7, 39–88.
- Helaouët, P., Beaugrand, G., 2007. Macroecology of *Calanus finmarchicus* and *C. helgolandicus* in the North Atlantic Ocean and adjacent seas. *Marine Ecology Progress Series* 345, 147–165.
- Helaouët, P., Beaugrand, G., 2009. Physiology, ecological niches and species distribution. *Ecosystems* 12, 1235–1245.
- Helaouët, P., Beaugrand, G., Reid, P.C., 2011. Macrophysiology of *Calanus finmarchicus* in the North Atlantic Ocean. *Progress in Oceanography* 91, 217–228.
- Henson, S.A., Robinson, I., Allen, J.T., Waniek, J.J., 2006. Effect of meteorological conditions on interannual variability in timing and magnitude of the spring bloom in the Irminger Basin, North Atlantic. *Deep-Sea Research Part I* 53, 1601–1615.
- Herman, A.W., Sameoto, D.D., Shunian, C., Mitchell, M.R., Petrie, B., Cochrane, B., 1991. Sources of zooplankton on the Nova Scotia Shelf and their aggregations within deep shelf basins. *Continental Shelf Research* 8, 205–221.
- Hijmans, R.J., Elith, J., 2013. Species distribution modeling with R. <http://cran.r-project.org/web/packages/dismo/vignettes/sdm.pdf>.
- Hind, A., Gurney, W.S.C., Heath, M., Bryant, A.D., 2000. Overwintering strategies in *Calanus finmarchicus*. *Marine Ecology Progress Series* 193, 95–107.
- Hirche, H.J., 1991. Distribution of dominant Calanoid copepod species in the Greenland Sea during late fall. *Polar Biology* 11, 351–362.
- Hirche, H.J., 1996a. Diapause in the marine copepod, *Calanus finmarchicus* – a review. *Ophelia* 44, 129–143.
- Hirche, H.-J., 1996b. The reproductive biology of the marine copepod, *Calanus finmarchicus* – a review. *Ophelia* 44, 111–128.
- Hirche, H.J., 1997. Life cycle of the copepod *Calanus hyperboreus* in the Greenland Sea. *Marine Biology* 128, 607–618.
- Hirche, H.J., Meyer, U., Niehoff, B., 1997. Egg production of *Calanus finmarchicus*: effect of temperature, food and season. *Marine Biology* 127, 609–620.
- Hirche, H.J., Brey, T., Niehoff, B., 2001. A high-frequency time series at ocean Weather ship station M (Norwegian Sea): population dynamics of *Calanus finmarchicus*. *Marine Ecology Progress Series* 219, 205–219.
- Hirzel, A.H., Hausser, J., Chessel, D., Perrin, N., 2002. Ecological-niche factor analysis: how to compute habitat-suitability maps without absence data? *Ecology* 83, 2027–2036.
- Hjollo, S.S., Huse, G., Skogen, M.D., Melle, W., 2012. Modelling secondary production in the Norwegian Sea with a fully coupled physical/primary production/individual-based *Calanus finmarchicus* model system. *Marine Biology Research* 8, 508–526.
- Hop, H., Falk-Petersen, S., Svendsen, H., Kwasniewski, S., Pavlov, V., Pavlova, O., Soreide, J.E., 2006. Physical and biological characteristics of the pelagic system across Fram Strait to Kongsfjorden. *Progress in Oceanography* 71, 182–231.
- Huse, G., Budgell, W., Melle, W., Skogen, M., Svendsen, E., submitted for publication. A 3d super-individual model with emergent life history and behaviour for *Calanus finmarchicus* in the Norwegian Sea. *Ecological Modelling*.
- Huse, G., Holst, J.C., Utne, K., Nottestad, L., Melle, W., Slotte, A., Ottersen, G., Fenchel, T., Uiblein, F., 2012. Effects of interactions between fish populations on ecosystem dynamics in the Norwegian Sea – results of the INFERNO project Preface. *Marine Biology Research* 8, 415–419.
- Irigoien, X., 2000. Vertical distribution and population structure of *Calanus finmarchicus* at station India (59 degrees N, 19 degrees W) during the passage of the great salinity anomaly, 1971–1975. *Deep-Sea Research Part I* 47, 1–26.
- Irigoien, X., 2004. Some ideas about the role of lipids in the life cycle of *Calanus finmarchicus*. *Journal of Plankton Research* 26, 259–263.
- Irigoien, X., Chust, G., Fernandes, J.A., Albaina, A., Zarauz, L., 2011. Factors determining mesozooplankton species distribution and community structure in shelf and coastal waters. *Journal of Plankton Research* 33, 1182–1192.
- Irigoien, X., Harris, R.P., 2006. Comparative population structure, abundance and vertical distribution of six copepod species in the North Atlantic: evidence for intraguild predation? *Marine Biology Research* 2, 276–290.
- Irigoien, X., Head, R., Klenke, U., Meyer-Harms, B., Harbour, D., Niehoff, B., Hirche, H.-J., Harris, R., 1998. A high frequency time series at weather ship M, Norwegian Sea, during the 1997 spring bloom: feeding of adult female *Calanus finmarchicus*. *Marine Ecology Progress Series* 172, 127–137.
- Isaaks, E.H., Srivastava, M.R., 1989. *Applied Geostatistics*. Oxford University Press, Oxford, England, 561pp.
- Ji, R., Ashjian, C.J., Campbell, R.C., Chen, C., Gao, G., Davis, C.S., Cowles, G.W., Beardsley, R.C., 2012. Life history and biogeography of *Calanus* copepods in the Arctic Ocean: an individual-based modeling study. *Progress in Oceanography* 96, 40–56.
- Ji, R., Edwards, M., Mackas, D., Runge, J., Thomas, A., 2010. Marine plankton phenology and life history in a changing climate: current research and future directions. *Journal of Plankton Research* 32, 1355–1368.
- Johnson, C.L., Leising, A.W., Runge, J.A., Head, E.J.H., Pepin, P., Plourde, S., Durbin, E.G., 2008. Characteristics of *Calanus finmarchicus* dormancy patterns in the Northwest Atlantic. *ICES Journal of Marine Science* 65, 339–350.
- Jonas, T.D., Walne, A., Beaugrand, G., Gregory, L., Hays, G.C., 2004. The volume of water filtered by a CPR: the effect of ship speed. *Journal of Plankton Research* 26, 1499–1506.
- Jónasdóttir, S.H., Gudfinnsson, H.G., Gislason, A., Astthorsson, O.S., 2002. Diet composition and quality for *Calanus finmarchicus* egg production and hatching success off south-west Iceland. *Marine Biology* 140, 1195–1206.
- Jónasdóttir, S.H., Koski, M., 2011. Biological processes in the North Sea: comparison of *Calanus helgolandicus* and *Calanus finmarchicus* vertical distribution and production. *Journal of Plankton Research* 33, 85–103.
- Jónasdóttir, S.H., Richardson, K., Heath, M.R., Ingvarsdóttir, A., Christoffersen, A., 2008. A spring production of *Calanus finmarchicus* at the Iceland-Scotland Ridge. *Deep-Sea Research Part I* 55, 471–489.
- Jónasdóttir, S.H., Trung, N.H., Hansen, F., Gärtner, S., 2005. Egg production and hatching success in the calanoid copepods *Calanus helgolandicus* and *Calanus finmarchicus* in the North Sea from March to September 2001. *Journal of Plankton Research* 27, 1239–1259.
- Kjellerup, S., Dunweber, M., Swalethorp, R., Nielsen, T.G., Møller, E.F., Markager, S., Hansen, B.W., 2012. Effects of a future warmer ocean on the coexisting copepods *Calanus finmarchicus* and *C. glacialis* in Disko Bay, western Greenland. *Marine Ecology Progress Series* 447, 87–132.
- Korzukhin, M.D., Ter-Mikaelian, M.T., Wagner, R.G., 1996. Process versus empirical models: which approach for forest ecosystem management? *Canadian Journal of Forest Research* 26, 879–887.
- Laabir, M., Poulet, S.A., Ianora, A., 1995. Measuring production and viability of eggs in *Calanus helgolandicus*. *Journal of Plankton Research* 17, 1125–1142.
- Landry, M.R., 1981. Switching between herbivory and carnivory by the planktonic marine copepod *Calanus pacificus*. *Marine Biology* 65, 77–82.

- Langøy, H., Nøttestad, L., Skaret, G., Broms, C., Fernö, A., 2012. Overlap in distribution and diets of Atlantic mackerel (*Scomber scombrus*), Norwegian spring-spawning herring (*Clupea harengus*) and blue whiting (*Micromesistius poutassou*) in the Norwegian Sea during late summer. *Marine Biology Research* 8, 442–460.
- Levinson, H., Turner, J.T., Nielsen, T.G., Hansen, B.W., 2000. On the trophic coupling between protists and copepods in Arctic marine Ecosystems. *Marine Ecology Progress Series* 204, 65–77.
- Loder, J.W., Petrie, B., Gawarkiewicz, G., 1998. The coastal ocean off northeast North America: a large-scale view. In: Robinson, A.R., Brink, K.H. (Eds.), *The Sea. The Global Coastal Ocean. Regional Studies and Synthesis*, vol. 11. John Wiley and Sons, Inc., New York, pp. 125–134.
- Longhurst, A., 1998. *Ecological Geography of the Sea*. Academic Press, London.
- Lynch, D.R., Gentleman, W.C., McGillicuddy Jr., D.J., Davis, C.S., 1998. Biological/physical simulations of *Calanus finmarchicus* population dynamics in the Gulf of Maine. *Marine Ecology Progress Series* 169, 189–210.
- Mahavedan, A., D'Asaro, E., Lee, C., Perry, M.J., 2012. Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms. *Science* 337, 54–58.
- Maps, F., Plourde, S., Zakardjian, B., 2010. Control of dormancy by lipid metabolism in *Calanus finmarchicus*: a population model test. *Marine Ecology Progress Series* 403, 165–180.
- Maps, F., Runge, J., Leising, A., Pershing, A., Record, N., Plourde, S., Pierson, J., 2012. Modeling the timing and duration of dormancy in populations of *Calanus finmarchicus* on the northwest Atlantic shelf. *Journal of Plankton Research* 34, 36–54.
- Maps, F., Zakardjian, B., Plourde, S., Saucier, F.J., 2011. Modeling the interactions between the seasonal and diel migration behaviors of *Calanus finmarchicus* and the circulation in the Gulf of St. Lawrence (Canada). *Journal of Marine Systems* 88, 183–202.
- Marshall, S.M., Orr, A.P., 1972. *The Biology of a Marine Copepod Calanus finmarchicus* Gunnerus. Reprint (with a new preface by S.M. Marshall). Springer Verlag, Berlin.
- McLaren, I.A., Head, E., Sameoto, D.D., 2001. Life cycles and seasonal distributions of *Calanus finmarchicus* on the central Scotian Shelf. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 659–670.
- Meise, C.J., O'Reilly, J.E., 1996. Spatial and seasonal patterns in the abundance and age-composition of *Calanus finmarchicus* in the Gulf of Maine and on Georges Bank, 1977–1987. *Deep-Sea Research Part II* 43, 1473–1501.
- Melle, W., Ellertsen, B., Skjoldal, H.R., 2004. Zooplankton: the link to higher trophic levels. In: Skjoldal, H.R. (Ed.), *The Norwegian Sea Ecosystem*. Tapir, Trondheim, pp. 137–202.
- Melle, W., Skjoldal, H.R., 1989. Zooplankton reproduction in the Barents Sea: vertical distribution of eggs and nauplii of *Calanus finmarchicus* in relation to spring phytoplankton development. In: Ryland, J.S., Tyler, P. (Eds.), *Reproduction, Genetics and Distributions of Marine Organisms*. Olsen & Olsen, Copenhagen, pp. 137–145.
- Melle, W., Skjoldal, H.R., 1998. Spawning and development of *Calanus* spp. in the Barents Sea. *Marine Ecology Progress Series* 169, 211–228.
- Miller, C.B., Cowles, T.J., Wiebe, P.H., Copley, N.J., Grigg, H., 1991. Phenology in *Calanus-finmarchicus* – hypotheses about control mechanisms. *Marine Ecology Progress Series* 72, 79–91.
- Miller, C.B., Lynch, D.R., Carlotti, F., Gentleman, W., Lewis, C.V.W., 1998. Coupling of an individual-based population dynamic model of *Calanus finmarchicus* to a circulation model for the Georges Bank region. *Fisheries Oceanography* 7, 219–234.
- Møller, E.F., Maar, M., Jonasdottir, S.H., Nielsen, T.G., Tonnesson, K., 2012. The effect of changes in temperature and food on the development of *Calanus finmarchicus* and *Calanus helgolandicus* populations. *Limnology and Oceanography* 57, 211–220.
- Muñoz, M.E.S., Giovanni, R., Siqueira, M.F., Sutton, T., Brewer, P., Pereira, R.S., Canhos, D.A.L., Canhos, V.P., 2009. OpenModeller: a generic approach to species' potential distribution modelling. *Geoinformatica*. <http://dx.doi.org/10.1007/s10707-009-0090-7>.
- Neuheimer, A.B., Gentleman, W.C., Pepin, P., Head, E.J.H., 2010. How to build and use individual-based models (IBMs) as hypothesis testing tools. *Journal of Marine Systems* 81, 122–133.
- Nichols, J.H., Thompson, A.B., 1991. Mesh selection of copepodite and nauplius stages of four calanoid copepod species. *Journal of Plankton Research* 13, 661–671.
- Niehoff, B., 2004. The effect of food limitation on gonad development and egg production of the planktonic copepod *Calanus finmarchicus*. *Journal of Experimental Marine Biology and Ecology* 307, 237–259.
- Niehoff, B., Klenke, U., Hirche, H.J., Irigoien, X., Head, R., Harris, R., 1999. A high frequency time series at Weathership M, Norwegian Sea, during the 1997 spring bloom: the reproductive biology of *Calanus finmarchicus*. *Marine Ecology Progress Series* 176, 81–92.
- Niehoff, B., Madsen, S.D., Hansen, B.W., Nielsen, T.G., 2002. Reproductive cycles of three dominant *Calanus* species in Disko Bay, West Greenland. *Marine Biology* 140, 567–576.
- Nix, H.A., 1986. BIOCLIM – a Bioclimatic Analysis and Prediction System. Research report, CSIRO Division of Water and Land Resources, 1983–1985, 59–60.
- Ohman, M.D., 2012. Estimation of mortality for stage-structured zooplankton populations: what is to be done? *Journal of Marine Systems* 93, 4–10.
- Ohman, M.D., Eiane, K., Durbin, E.G., Runge, J.A., Hirche, H.-J., 2004. A comparative study of *Calanus finmarchicus* mortality patterns at five localities in the North Atlantic. *ICES Journal of Marine Science* 61, 687–697.
- Ohman, M.D., Hirche, H.J., 2001. Density-dependent mortality in an oceanic copepod population. *Nature* 412, 638–641.
- Ohman, M.D., Runge, J.A., 1994. Sustained fecundity when phytoplankton resources are in short supply: omnivory by *Calanus finmarchicus* in the Gulf of St. Lawrence. *Limnology and Oceanography* 39, 21–36.
- Ohman, M.D., Runge, J.A., Durbin, E.G., Field, D.B., Niehoff, B., 2002. On birth and death in the sea. *Hydrobiologia* 480, 55–68.
- Ohman, M.D., Sullivan, B.K., Durbin, E.G., Runge, J.A., 2008. Relationship of predation potential to mortality for *Calanus finmarchicus* on Georges Bank, N.W. Atlantic. *Limnology and Oceanography* 53, 1643–1655.
- Olsen, E.M., Melle, W., Kaartvedt, S., Holst, J.C., Mork, K.A., 2007. Spatially structured interactions between a migratory pelagic predator, the Norwegian spring-spawning herring *Clupea harengus* L., and its zooplankton prey. *Journal of Fish Biology* 70, 799–815.
- O'Reilly, J.E., Evans-Zetlin, C., Busch, D.A., 1987. Primary production. In: Backus, R.H. (Ed.), *Georges Bank*. MIT Press, Cambridge MA, pp. 221–233.
- O'Reilly, J.E., Zetlin, C., 1998. Seasonal, horizontal, and vertical distribution of phytoplankton chlorophyll a in the northeast U.S. continental shelf ecosystem. NOAA Technical Report NMFS 139, 120 pp.
- Østvedt, O.-J., 1955. Zooplankton investigations from Weather Ship M in the Norwegian Sea, 1948–1949. *Hvalradets Skrifter* 40, 1–93.
- Overholtz, W.J., Link, J.S., 2007. Consumption impacts by marine mammals, fish, and seabirds on the Gulf of Maine-Georges Bank Atlantic herring (*Clupea harengus*) complex during the years 1977–2002. *ICES Journal of Marine Science* 64, 83–96.
- Pepin, P., 2013. Distribution and feeding of *Benthosema glaciale* in the western Labrador Sea: fish-zooplankton interaction and the consequence to calanoid copepod populations. *Deep-Sea Research I* 75, 119–134.
- Pepin, P., Han, G., Head, E., 2013. Modelling the dispersal of *Calanus finmarchicus* on the Newfoundland Shelf: implications for the analysis of population dynamics from a high frequency monitoring site. *Fisheries Oceanography* 22, 371–387.
- Pepin, P., Parrish, C.C., Head, E.J.H., 2011. Late autumn condition of *Calanus finmarchicus* in the northwestern Atlantic: evidence of size-dependent differential feeding. *Marine Ecology Progress Series* 423, 155–166.
- Petersen, O.-P., Tande, K.S., Timonin, A., Semenova, T., 2000. A possible connection between hydrography and the distribution of *Calanus finmarchicus* on the Norwegian midshelf in 1997. *ICES Journal of Marine Science* 57, 1645–1655.
- Petrie, B., Drinkwater, K., 1993. Temperature and salinity variability on the Scotian Shelf and in the Gulf of Maine 1945–1990. *Journal of Geophysical Research* 98, 20079–20089.
- Pierson, J.J., Batchelder, H., Saumweber, W., Leising, A., Runge, J., 2013. The impact of increasing temperatures on dormancy duration in *Calanus finmarchicus*. *Journal of Plankton Research* 35 (3), 504–512.
- Planque, B., Fromentin, J.M., 1996. *Calanus* and environment in the eastern North Atlantic. I. Spatial and temporal patterns of *C. finmarchicus* and *C. helgolandicus*. *Marine Ecology Progress Series* 134, 101–109.
- Planque, B., Hays, G.C., Ibanez, F., Gamble, J.C., 1997. Large scale spatial variations in the seasonal abundance of *Calanus finmarchicus*. *Deep-Sea Research Part I* 44, 315–326.
- Platt, T., Sathyendranath, S., Forget, M.-H., White III, G.N., Caverhill, C., Bouman, H., Devred, E., Son, S.H., 2008. Operational estimation of primary production at large geographical scales. *Remote Sensing of Environment* 112, 3437–3448.
- Platt, T., Sathyendranath, S., White III, G.N., Fuentes-Yaco, C., Zhai, L., Devred, E., Tang, C., 2010. Diagnostic properties of phytoplankton time series from remote sensing. *Estuaries and Coasts* 33, 428–439.
- Plourde, S., Joly, P., 2008. Comparison of in situ egg production rate in *Calanus finmarchicus* and *Metridia longa*: discriminating between methodological and species-specific effects. *Marine Ecology Progress Series* 363, 165–175.
- Plourde, S., Joly, P., Runge, J.A., Dodson, J., Zakardjian, B., 2003. Life cycle of *Calanus hyperboreus* in the lower St. Lawrence Estuary and its relationship to local environmental conditions. *Marine Ecology Progress Series* 255, 219–233.
- Plourde, S., Joly, P., Runge, J.A., Zakardjian, B., Dodson, J.J., 2001. Life cycle of *Calanus finmarchicus* in the lower St. Lawrence Estuary: the imprint of circulation and late timing of the spring phytoplankton bloom. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 647–658.
- Plourde, S., Maps, F., Joly, P., 2009a. Mortality and survival in early stages control recruitment in *Calanus finmarchicus*. *Journal of Plankton Research* 31, 371–388.
- Plourde, S., Pepin, P., Head, E., 2009b. Long-term seasonal and spatial patterns in mortality and survival of *Calanus finmarchicus* across the Atlantic Zone Monitoring Program region. Northwest Atlantic. *ICES Journal of Marine Science* 66, 1942–1958.
- Plourde, S., Runge, J., 1993. Reproduction of the planktonic copepod *Calanus finmarchicus* in the Lower St. Lawrence Estuary: relation to the cycle of phytoplankton production and evidence for a *Calanus* pump. *Marine Ecology Progress Series* 102, 217–227.
- Prokopcuk, I., Sentyabov, E., 2006. Diets of herring, mackerel, and blue whiting in the Norwegian Sea in relation to *Calanus finmarchicus* distribution and temperature conditions. *ICES Journal of Marine Science* 63, 117–127.
- Provan, J., Beatty, G.E., Keating, S.L., Maggs, C.A., Savidge, G., 2009. High dispersal potential has maintained long-term population stability in the North Atlantic copepod *Calanus finmarchicus*. *Proceedings of the Royal Society B: Biological Sciences* 276, 301–307.
- Record, N., Pershing, A., Runge, J., Mayo, C., Monger, B., Chen, C., 2010. Improving ecological forecasts with genetic algorithms: an application to a copepod community model. *Journal of Marine Systems* 82, 96–110.
- Reverdin, G., Niiler, P.P., Valdimarsson, H., 2003. North Atlantic Ocean surface currents. *Journal of Geophysical Research* 108, 1–21.

- Rey, F., 2004. Phytoplankton: the grass of the sea. In: Skjoldal, H.R. (Ed.), The Norwegian Sea Ecosystem. Tapir, Trondheim, pp. 97–136.
- Rey, C., Carloti, F., Tande, K., Hygum, B.H., 1999. Egg and faecal pellet production of female *Calanus finmarchicus* from controlled mesocosms and in situ populations: influence of age and feeding history. Marine Ecology Progress Series 188, 133–148.
- Rey-Rassat, C., Irigoien, X., Harris, R., Carloti, F., 2002. Energetic cost of gonad development in *Calanus finmarchicus* and *C. helgolandicus*. Marine Ecology Progress Series 238, 301–306.
- Reygondeau, G., Beaugrand, G., 2011. Future climate-driven shifts in distribution of *Calanus finmarchicus*. Global Change Biology 17, 756–766.
- Richardson, A.J., Walne, A.W., John, A.W.G., Jonas, T.D., Lindley, J.A., Sims, D.W., Stevens, D., Witt, M., 2006. Using continuous plankton recorder data. Progress in Oceanography 68, 27–74.
- Richardson, K., Jónasdóttir, S.H., Hay, S.J., Christoffersen, A., 1999. *Calanus finmarchicus* egg production and food availability in the Faroe-Shetland Channel and northern North Sea: October–March. Fisheries Oceanography 8 (Suppl. 1), 153–162.
- Runge, J.A., 1987. Measurements of egg production rate of *Calanus finmarchicus* from preserved samples. Canadian Journal of Fisheries and Aquatic Sciences 44, 2009–2012.
- Runge, J.A., de Lafontaine, Y., 1996. Characterization of a pelagic food web in the northern Gulf of St. Lawrence: the larval redfish-*Calanus*-microplankton interaction. Fisheries Oceanography 5, 21–37.
- Runge, J.A., Plourde, S., 1996. Fecundity characteristics of *Calanus finmarchicus* in coastal waters of eastern Canada. Ophelia 44, 171–187.
- Runge, J.A., Roff, J.C., 2000. The measurement of growth and reproductive rates. In: Harris, R., Wiebe, P., Lenz, J., Skjoldal, H.R., Huntley, M. (Eds.), ICES Zooplankton Methodology Manual. Academic Press, New York, pp. 401–454.
- Runge, J.A., Franks, P.J., Gentleman, W.C., Megrey, B.A., Rose, K.A., Werner, F.E., Zakardjian, B. (Eds.), 2005. Diagnosis and Prediction of Variability in Secondary Production and Fish Recruitment Processes: Developments in Physical-Biological Modeling. Harvard University Press.
- Runge, J.A., Plourde, S., Joly, P., Niehoff, B., Durbin, E., 2006. Characteristics of egg production of the planktonic copepod, *Calanus finmarchicus*, on Georges Bank: 1994–1999. Deep-Sea Research Part II 53, 2618–2631.
- Sameoto, D.D., Herman, A.W., 1990. Life cycles and distribution of *Calanus finmarchicus* in deep basins on the Nova Scotia shelf and seasonal changes in *Calanus* spp. Marine Ecology Progress Series 66, 225–237.
- Samuelson, A., Huse, G., Hansen, C., 2009. Shelf recruitment of *Calanus finmarchicus* off the west coast of Norway: role of physical processes and timing of diapause termination. Marine Ecology Progress Series 386, 163–180.
- Saumweber, W.J., Durbin, E.G., 2006. Estimating potential diapause duration in *Calanus finmarchicus*. Deep-Sea Research Part II 53, 2597–2617.
- Skjoldal, H.R., 2004. The Norwegian Sea Ecosystem. Tapir, Trondheim.
- Skjoldal, H.R., Dalpadado, P., Dommasnes, A., 2004. Food webs and trophic interactions. In: Skjoldal, H.R. (Ed.), The Norwegian Sea Ecosystem. Tapir Academic, Trondheim, Norway, pp. 447–506.
- Slagstad, D., Tande, K.S., 1996. The importance of seasonal vertical migration in across shelf transport of *Calanus finmarchicus*. Ophelia 44, 189–205.
- Slagstad, D., Tande, K.S., 2007. Structure and resilience of overwintering habitats of *Calanus finmarchicus* in the Eastern Norwegian Sea. Deep-Sea Research Part II 54, 2702–2715.
- Smith, B.E., Link, J.S., 2010. The trophic dynamics of 50 finfish and 2 squid species on the northeast U.S. Continental Shelf. NOAA Tech. Mem. NMFS-NE-216, 1–646.
- Soreide, J.E., Falk-Petersen, S., Hegseth, E.N., Hop, H., Carroll, M.L., Hobson, K.A., Blachowiak-Samolyk, K., 2008. Seasonal feeding strategies of *Calanus* in the high-Arctic Svalbard region. Deep-Sea Research Part II 55, 2225–2244.
- Speirs, D.C., Gurney, W.S.C., Heath, M.R., Wood, S.N., 2005. Modelling the basin-scale demography of *Calanus finmarchicus* in the north-east Atlantic. Fisheries Oceanography 14, 333–358.
- Speirs, D.C., Gurney, W.S.C., Heath, M.R., Horbelt, W., Wood, S.N., de Cuevas, B.A., 2006. Ocean-scale modelling of the distribution, abundance and seasonal dynamics of the copepod *Calanus finmarchicus*. Marine Ecology Progress Series 313, 173–192.
- Speirs, D.C., Gurney, W.S.C., Holmes, S.J., Heath, M.R., Wood, S.N., Clarke, E.D., Harms, I.H., Hirche, H.J., McKenzie, E., 2004. Understanding demography in an advective environment: modelling *Calanus finmarchicus* in the Norwegian Sea. Journal of Animal Ecology 73, 897–910.
- Stenevik, E.K., Melle, W., Gaard, E., Gislason, A., Broms, C.T.A., Prokopchuk, I., Ellertsen, B., 2007. Egg production of *Calanus finmarchicus* – a basin-scale study. Deep-Sea Research Part II 54, 2672–2685.
- Sverdrup, H.U., 1953. On conditions for the vernal bloom of phytoplankton. Journal du Conseil permanent International pour l'Exploration de la Mer 18, 287–295.
- Swalethorp, R., Kjellerup, S., Dünweber, M., Nielsen, T.G., Möller, E.F., Rysgaard, S., Hansen, B.W., 2011. Production of *Calanus finmarchicus*, *C. glacialis* and *C. hyperboreus* in Disko Bay, western Greenland, with emphasis on life strategy. Marine Ecology Progress Series 429, 125–144.
- Tande, K.S., 1982. Ecological investigations on the zooplankton community of Balsfjorden, Northern Norway – generation cycles, and variations in body-weight and body content of carbon and nitrogen related to overwintering and reproduction in the copepod *Calanus finmarchicus* (Gunnerus). Journal of Experimental Marine Biology and Ecology 62, 129–142.
- Tande, K.S., Miller, C.B., 2000. Population dynamics of *Calanus* in the North Atlantic: results from the Trans-Atlantic study of *Calanus finmarchicus*. ICES Journal of Marine Science 57, 1527.
- Tarrant, A.M., Baumgartner, M.F., Verslycke, T., Johnson, C.L., 2008. Differential gene expression in diapausing and active *Calanus finmarchicus* (Copepoda). Marine Ecology Progress Series 355, 193–207.
- Thomas, A.C., Townsend, D.W., Weatherbee, R., 2003. Satellite-measured phytoplankton variability in the Gulf of Maine. Continental Shelf Research 23, 971–989.
- Thuiller, W., Lafourcade, B., Engler, R., Araujo, M.B., 2009. BIOMOD – a platform for ensemble forecasting of species distributions. Ecography 32, 369–373.
- Tittensor, D.P., deYoung, B., Tang, C.L., 2003. Modelling the distribution, sustainability and diapause emergence timing of the copepods *Calanus finmarchicus* in the Labrador Sea. Fisheries Oceanography 12, 299–316.
- Torgersen, T., Huse, G., 2005. Variability in retention of *Calanus finmarchicus* in the Nordic Seas. ICES Journal of Marine Science 62, 1301–1309.
- Unal, E., Bucklin, A., 2010. Basin-scale population genetic structure of the planktonic copepod *Calanus finmarchicus* in the North Atlantic Ocean. Progress in Oceanography 87, 175–185.
- Utne, K.R., Hjollo, S.S., Huse, G., Skogen, M., 2012. Estimating the consumption of *Calanus finmarchicus* by planktivorous fish in the Norwegian Sea using a fully coupled 3D model system. Marine Biology Research 8, 527–547.
- Valle, M., Borja, Á., Chust, G., Galparsoro, I., Garmendia, J.M., 2011. Modelling suitable estuarine habitats for *Zostera noltii*, using Ecological Niche Factor Analysis and Bathymetric LiDAR. Estuaries, Coasts and Shelf Science 94, 144–154.
- Vidal, J., 1980. Physioecology of zooplankton. 2. Effects of phytoplankton concentration, temperature, and body size on the development and molting rates of *Calanus pacificus* and *Pseudocalanus* sp.. Marine Biology 56, 135–146.
- Wagner, M.M., Durbin, E.G., Buckley, L.J., 1998. RNA:DNA ratios as indicators of nutritional condition in the copepod *Calanus finmarchicus*. Marine Ecology Progress Series 162, 173–181.
- Waniewski, J., Holliday, N.P., 2006. Large-scale physical controls on phytoplankton growth in the Irminger Sea, Part II: Model study of the physical and meteorological preconditioning. Journal of Marine Systems 59, 219–237.
- Warner, A.J., Hays, G.C., 1994. Sampling by the Continuous Plankton Recorder survey. Progress in Oceanography 34, 237–256.
- White, J.R., Roman, M.R., 1992. Egg production by the calanoid copepod *Acartia tonsa* in the mesohaline Chesapeake Bay: the importance of food resources and temperature. Marine Ecology Progress Series 86, 239–249.
- Williams, R., 1985. Vertical distribution of *Calanus finmarchicus* and *C. helgolandicus* in relation to the development of the seasonal thermocline in the Celtic Sea. Marine Biology 86, 145–149.
- Zakardjian, B., Sheng, A.J., Runge, J.A., Thompson, K.R., Gratton, Y., McLaren, I.A., Plourde, S., 2003. Effects of temperature and circulation on the population dynamics of *Calanus finmarchicus* in the Gulf of St. Lawrence and Scotian Shelf: study with a coupled three-dimensional hydrodynamic, stage-based life-history model. Journal of Geophysical Research 108 (C11), 8016.
- Zhai, L., Platt, T., Tang, C., Sathyendranath, S., Hernández Walls, R., 2011. Phytoplankton phenology on the Scotian Shelf. ICES Journal of Marine Science 68, 781–791.
- Zhai, L., Gudmundsson, K., Miller, P., Peng, W.J., Gudfinnsson, H., Debes, H., Hatun, H., White, G.N., Walls, R.H., Sathyendranath, S., Platt, T., 2012. Phytoplankton phenology and production around Iceland and Faroes. Continental Shelf Research 37, 15–25.
- Zhi-Ping, M., Saucier, F.J., Le Fouest, V., Zakardjian, B., Sennville, S., Xie, H., Starr, M., 2010. Modeling the timing of the spring phytoplankton bloom and biological production of the Gulf of St. Lawrence (Canada): effects of colored dissolved organic matter and temperature. Continental Shelf Research 30, 2027–2042.